Landfill Remediation Project Manager's Handbook

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Air Force Center for Environmental Excellence
Technology Transfer Division
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3207 North Road
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Innovative Technology in the Public Interest™

Center for Science and Technology
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Preface

This document is part of a series that focuses on innovative Air Force landfill remediation. Other documents in the series provide information and references from the current literature on state-of-the-art landfill remediation technologies and regulations [45], identify the characteristics of Air Force landfills [43], provide a screening tool for selecting landfill cover alternatives [44], and evaluate computer models that are currently being used for landfill cover design [46].

This document provides Air Force Remedial Project Managers (RPMs) with guidance through the steps leading to remediation of a landfill site. Each step is discussed in the context of the information RPMs will need to manage the project. The decisions required to determine whether the EPA presumptive remedy of containment is appropriate and which containment components are needed are described in detail using the *Decision Tool for Landfill Remediation* [44] in conjunction with this document. The principal sections of this document discuss the following:

- Regulatory framework surrounding landfill covers
- Information required to characterize the landfill site and design the remediation
- Determination of the remediation requirements
- Development of alternatives
- Design of the remediation
- Providing long-term maintenance and monitoring.

This document is intended to provide informative and practical guidance on the design of Air Force landfill covers. In most cases, the RPM will be overseeing the work of the contractor(s) who will perform the field investigation, design the needed facilities, install the remediation, and provide long-term maintenance and monitoring. Therefore, recent texts are referenced that provide detailed information about designing conventional landfill components and other related topics; design details are provided only for innovative concepts that are not well documented elsewhere.

While the major components of a landfill remediation are all addressed in this document, the chapters on alternatives selection and design primarily focus on landfill covers and their components. The selection and implementation of innovative technologies are emphasized throughout this document. Some of these innovative designs have the potential to be effective at many Air Force landfills and could result in a significant reduction in remediation costs.

Table of Contents

Section **Page**

List of Figures

List of Tables

1 Introduction

The environmental era during the 1970s in the United States brought with it a new appreciation for the adverse and chronic effects of solid waste disposal practices. Even the development of "sanitary" landfills decades earlier did little to protect the underground environment; instead, the approach focused primarily on disease prevention and aesthetic concerns. During this time, specific environmental objectives evolved that drastically changed the design concept for landfills, and legislation was enacted by the federal government and the states with the intention of preventing and mitigating pollution from landfill sites. Today, both the technical design of landfills and the applicable regulatory requirements are complex.

This document guides Remedial Project Managers (RPMs) through the principal steps leading to remediation of a landfill site. Each step is discussed in the context of the information RPMs will need to manage the project. The decisions required to determine whether the Environmental Protection Agency's (EPA's) presumptive remedy of containment is appropriate and which containment components are needed are described in detail using the *Decision Tool for Landfill Remediation* (Decision Tool) [44], which is another in this series of documents concerning military landfills.

This document is intended to provide informative and practical guidance on the design of Air Force landfill covers. In most cases, the RPM will be overseeing the work of the contractor(s) who will (1) perform the field investigation, (2) design and install the needed facilities, and (3) provide long-term maintenance and monitoring. Therefore, the reader is referred to recent texts that offer detailed information about designing conventional landfill components and other related topics; design details are provided only for innovative concepts that are not well documented elsewhere.

The alternatives selection and design sections primarily focus on landfill covers and their components. The cover is the most frequently required component if the "No Further Action" alternative is not appropriate for a site. The landfill cover is also the most complex—and generally the most costly—component of a landfill remediation. The selection and implementation of innovative technologies is emphasized throughout this document. Recent articles in technical literature document that conventional barrier-type cover designs may be difficult to maintain over long periods of time; in addition, conventional covers are not proving to be as reliable as originally expected. Recent developments in innovative landfill cover design suggest that significant saving in installation costs—in some cases, more than 50 percent of the cost of a conventional design—may be achieved, along with improved long-term reliability.

Leachate collection and treatment, groundwater hydraulic control, and remediation of groundwater contamination are briefly discussed in this handbook but are not covered in detail. At modern landfills, a bottom liner is required for leachate collection, and both collection and treatment are designed and installed as part of the initial construction of the landfill. Very few Air Force installations still have operating landfills, and virtually all of the existing Air Force landfills are older facilities designed and constructed before the current regulations mandating bottom liners for leachate collection. Therefore, without a bottom liner and collection system, any regulatory requirement for leachate collection for treatment and/or disposal may require using extraction wells and trenches similar to a pump-and-treat system for groundwater remediation. In this handbook, the discussion of leachate collection and treatment focuses on groundwater extraction and on remediating leachate seeps.

1.1 Objectives

The Air Force has about 600 inactive landfills that will most likely require remediation. By extension, there are thousands of landfills with similar needs within the jurisdiction of the Department of Defense (DOD). Because of the expense and risk associated with other methods of dealing with landfill wastes, they are usually contained in place. Complete remediation may include installation of a properly designed surface cover, and depending upon site conditions, the remediation may also include collection and disposal of landfill gas, leachate collection and treatment, and hydraulic control of groundwater flowing under the landfill site.

Although other options exist and are discussed in this handbook, construction of a cover will most likely be the primary remedial action recommended for most Air Force landfills. One objective of this handbook is to provide the Air Force RPM with information and references on the selection, design, and construction of landfill remediation components. This information will help identify more cost-effective approaches to landfill remediation and ways to reduce remediation costs.

Landfill cover construction and maintenance are costly, and the cover type and performance affect all other remediation actions. Therefore, this handbook focuses primarily on the landfill cover. There are at least four important yet distinct reasons that provide the Air Force with incentive to obtain up-to-date information on the design and construction of landfill covers:

- Federal and state statutes mandate that each Air Force landfill must be (1) identified for no further action, (2) remediated, (3) removed, or (4) closed.
- Each landfill creates a potential risk to human health and the environment.
- Designing and constructing an effective landfill cover is complex and requires a team of engineers and scientists with a broad knowledge base.
- Conventional landfill covers are expensive, and the Air Force needs more cost-effective alternative covers that meet remediation requirements.

Although landfill-cover design and construction has become a sophisticated operation, it is also very expensive. Typical costs for conventional covers on Air Force bases vary from \$318,000 to \$570,000 per acre [43]; expenditures in the tens of millions of dollars for a single landfill are not uncommon. These costs are associated with technologies selected as much to conform to regulations as to satisfy scientific and engineering requirements or environmental concerns. In the past decade, innovative approaches to landfill covers have been proposed and demonstrated. Under the appropriate circumstances, these approaches offer the promise of providing effective environmental solutions at a lower cost. This handbook explores the cost-saving potential of these alternative technologies.

An RPM facing a landfill remediation will need to understand the two principal, but distinct, determinants of a practical, cost-effective solution: regulatory requirements and technical approaches. This handbook reflects a review of recent technical literature and regulations, and it will provide the reader with a basic understanding of the following:

- The regulatory framework that establishes landfill cover requirements
- Regulatory latitude for the selection of innovative landfill covers
- The purposes of landfill covers and the common components of landfill cover systems
- The primary factors that influence the selection and design of a landfill cover at a particular site
- State-of-the-art landfill cover designs

This handbook is organized into eight main sections including this introduction. Section 2 presents the regulatory framework that has controlled most of the landfill cover construction to date. As a practical matter, regulatory requirements are usually based on the Resource Conservation and Recovery Act (RCRA), but other pertinent federal legislation, directives, and policies are also discussed, and representative state regulations are reviewed. The handbook also discusses the approach required to gain regulatory acceptance of an innovative cover at a landfill site and the evaluation of landfill remediation options based upon risk and performance criteria. A review of current regulations governing landfills and of the recent literature concerning landfill covers was recently prepared and delivered to the Air Force as a separate document. For the convenience of the reader, much of the information from that document is incorporated into this handbook [45].

Section 3 of this handbook provides a technical overview of the components of a landfill remediation that will achieve environmental objectives. Various landfill cover designs are presented, and common landfill cover components are described. There is a clear commonality of purpose in these designs in spite of their different technical principles. Innovative approaches that can offer acceptable environmental protection at lower cost under the appropriate circumstances are also illustrated.

Section 4 describes the characterization of the site, as well as information typically required to develop remediation alternatives, design the remediation, and develop a long-term monitoring plan.

Section 5 describes the decision process used to determine whether the landfill site meets the definition of a municipal landfill and whether the EPA presumptive remedy of containment is appropriate. Other decisions include the remediation of hotspots and the selection of the necessary containment components. The *Decision Tool* [44] is referenced and used to guide the decision process. Remediation requirements are selected as the basis for developing remediation alternatives.

Section 6 of the handbook describes (1) the development of selected components into remediation alternatives, (2) the comparison of engineered alternatives with the "no further action" (NFA) alternative, and (3) the selection of a final remediation approach.

Section 7 describes the design of the remediation components and discusses significant design issues. The design of innovative approaches is discussed briefly in the handbook; for information on the detailed design of conventional landfill components, the reader is directed to consult recent textbooks on the subject.

Section 8 outlines the requirements for maintenance and long-term monitoring of the selected remediation.

A topical bibliography, assembled as a result of the literature review [45], has been expanded and is provided in Appendix F; it should be a useful reference for those interested in acquiring a more detailed understanding of the various topics presented here. A glossary of common landfill terms and a list of acronyms are also provided at the end of the handbook.

1.2 The Purpose of Landfill Containment

The application of containment—EPA's presumptive remedy—most often requires the design and installation of some form of landfill surface cover. Other components, such as landfill gas collection and disposal, groundwater treatment and/or containment, and the collection and disposal of leachates, may also be required.

There are fundamental scientific and technical reasons for placing a cover on a landfill site. Although regulations appear to drive the selection and design of landfill covers today, these regulations originated from specific environmental concerns and had a technical basis. Landfill covers seek to offer many environmental benefits, but they are based on three primary goals:

- **Minimizing infiltration**: Water that percolates through the waste may dissolve contaminants and form leachate, which can pollute both soil and groundwater as it travels from the site.
- **Isolating wastes**: A cover over the wastes prevents direct contact with potential receptors at the surface and controls movement of the waste material by wind or water.
- **Controlling landfill gases**: The uncontrolled release of explosive or toxic gases can create a potential hazard in the vicinity of a landfill.

These three goals are common to all landfill cover designs and will be reiterated throughout this document. The way in which they are technically implemented can be quite different and can significantly affect the cost of the remediation.

Landfill covers are intended to remain in place and provide protection to the environment for an extended period, perhaps centuries. However, most commonly used technologies have only been in existence for about 20 years. It is not known exactly how landfill cover performance will change over time. Innovative covers that do not rely on an impermeable barrier may offer more reliability in this respect.

Landfill gas collection may be required to safely dispose of explosive, and possibly toxic, landfill gas generated by the biodegradation of organic matter in the waste. It is especially important to control off-site migration of landfill gas when buildings or structures are located near the landfill site because of the danger of explosion from gas that might accumulate within or below the structure. However, the long-term operation and maintenance of an active gas collection and disposal system, if required, will be a significant financial burden.

The migration of landfill leachates into the groundwater may cause significant groundwater contamination. The resulting contaminant plume may require extensive, and expensive, remediation to restore the groundwater aquifer. If long-term operation and maintenance of leachate collection, treatment, and discharge is required, it will also impose a significant financial burden on the project.

1.3 Characteristics of Air Force Landfills

The selection and design of a landfill cover is necessarily specific to a particular site. Site-specific factors are discussed in greater detail in Section 3.1. However, military landfills —and Air Force landfills in particular—have common characteristics that set them apart from the commercial and municipal landfills in operation today.

In the past, military bases used landfills to dispose of solid wastes, including municipal waste, construction debris and rubble, industrial waste, cleaning solvents, paint strippers, and pesticides. The landfills at Air Force bases were usually constructed as trenches, pits, or other depressions in the earth into which the waste was deposited. Landfill contents, age of the waste, and construction methods impact the required remedial actions. While most present-day landfills are built with a complex bottom-liner system to collect leachate and prevent leakage into the underground environment, military landfills were generally constructed prior to the passage of RCRA and do not have a bottom liner. During the late 1980s, the Air Force shifted from depositing waste in landfills to contracting waste disposal; as a result, the majority of the Air Force landfills have been unused for many years. Much of the waste in these inactive landfills has already consolidated and decomposed, so surface subsidence in the cover will probably be small. Landfill gas production can also be expected to be low, so gas collection may not be necessary in the design of some alternative covers. These conditions could offer significant savings in both landfill construction and long-term operation costs.

Landfill contents, age of the waste, climate, and landfill construction methods all affect the choice of remedial actions. The Air Force Center for Environmental Excellence (AFCEE) landfill survey [43] included more than 40 percent of Air Force bases located within the continental United States (CONUS). The data reveal the following about Air Force landfills:

- About 86 percent of the landfills have been inactive for more than 20 years.
- Less than one percent of the landfills have bottom liners for leachate control.
- Remediation is complete for 23 percent of the surveyed landfills.
- The average surface area is about 13.3 acres.
- The climate at more than half of the bases surveyed is suitable for the installation of alternative covers.
- The remedial alternative of NFA was used a about 12 percent of the surveyed landfills.

These characteristics should be kept in mind while reading the remainder of the handbook. In particular, innovative landfill cover designs may have greater application at Air Force installations or other military sites than they have at landfill sites in general, and they may offer significant savings.

2 Regulations, Policies, and Processes

Federal and state regulations have long dictated not only the application of a landfill cover as a remedial alternative, but also its actual technical design. More recently, EPA has adopted policies that are meant to speed remediation and encourage the use of innovative designs. This section provides a view of the regulatory and policy impacts on landfill cover implementation and design, as well as a discussion of how to use this information to gain acceptance for the use of an innovative cover at Air Force sites.

The key federal legislation governing the closure of landfills was written in the early 1980s, and the beginning of the remediation programs for the correction of past disposal practices followed shortly thereafter. Section 2.1, Federal Regulation Framework, briefly discusses the primary federal regulations governing landfill closure. RCRA is the controlling federal law for both municipal solid waste (MSW) and hazardous waste (HW) landfills. For the most part, the remediation of old landfills is not addressed directly under RCRA, but it is regulated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). Under CERCLA, RCRA is the source of potential "applicable or relevant and appropriate requirements" (ARARs) that govern cleanup.

Currently, operating landfills at Air Force base are subject to the state's landfill regulations. Examples of state requirements are discussed in Section 2.2, State Regulation Framework. However, bases have few operating landfills today, so the closure of base landfills is generally conducted under the DOD's Environmental Restoration Program, following the CERCLA process, under which the RCRA and state regulations are considered as ARARs.

Given the prescriptive nature of RCRA and many state regulations, the intimate association among CERCLA, RCRA, and state regulations has historically been an impediment to the selection and installation of alternative landfill covers. However, the same association may also be interpreted as providing latitude to install alternative covers under the CERCLA process because of the flexibility in selecting ARARs. EPA, DOD, and the states are fully aware of this dichotomy and have expended considerable effort in defining and supporting the role of innovative technologies in the nation's remediation programs. To lay the groundwork for understanding this flexibility, various resources for the development and application of innovative technologies, specifically alternative landfill covers, are discussed in Section 2.3, EPA Directives and Other Resources for Innovative Technologies.

The process for guiding an Air Force RPM through this challenging regulatory environment toward the selection and implementation of an alternative cover is presented in Section 2.4, Latitude and Process for Alternative Technology, and in Section 2.5, General Approach for the Acceptance and Installation of an Innovative Cover.

Finally, a general concept for landfill closures is introduced in the Section 2.6, Risk-Based/Performance-Based Landfill Evaluation, which describes a purely technical basis for landfill closure. An Air Force RPM can use the resources, regulatory latitude, and acceptance process discussed in this section to gain acceptance of sound closure criteria at his/her base.

Each Air Force base is in a unique regulatory environment. The specific state regulations, the exact relationship between the federal and state regulators, and the priorities and concerns of the public make each landfill closure decision a singular process rather than a routine regulatory exercise. Understanding this situation from the outset will allow the RPM to guide the process to a technically sound, protective, and cost-effective closure decision.

2.1 Federal Regulation Framework

RCRA is the controlling federal law for both MSW and HW landfills. RCRA enforcement authority is delegated to the states as each state adapts equal or more stringent regulations than those contained in federal rules and regulations. Most states' regulations closely follow the RCRA regulations. RCRA contains many specific requirements regarding the construction, operation, and closure of a landfill, including surface water requirements, a groundwater contamination detection monitoring program, a closure system assessment monitoring program, closure criteria, and post-closure care requirements.

The remediation of old landfills is generally addressed under CERCLA rather than RCRA, with RCRA considered as an ARAR [69]. However, Air Force bases with active RCRA permits are exceptions because landfill remediation is addressed as a "corrective action" as a part of the RCRA permit requirement.

2.1.1 RCRA Landfill Closure Overview

RCRA divides landfills into two categories: HW landfills where hazardous wastes are disposed of in accordance with RCRA §264-Subtitle C Hazardous Wastes; and MSW landfills where only municipal wastes are disposed of in accordance with RCRA §258-Subtitle D Municipal Solid Waste.

At the time when RCRA was implemented, barrier-type covers using multiple low-permeability layers were considered the most permanent and protective landfill cover options. While the regulations allow for some design flexibility, both MSW and HW covers have specific permeability requirements reflecting this prejudice. For covers of HW landfills, Subtitle C states a general performance requirement to minimize migration of liquids through the closed landfill, while §264.310(a)(5) imposes a permeability requirement—the final cover must have a permeability less than or equal to the bottom liner or natural subsoils. Landfills with Subtitle C covers (§264.310[b][1] and [2]) are also required to operate and maintain a leachate collection system and a leak detection system (see Appendix A).

For MSW landfills with Subtitle D covers, this same duality exists in the general goal of minimizing infiltration (§258.60[a]) and in the specific requirement that the permeability of the final cover be less than or equal to the permeability of any bottom-liner system or the natural subsoils, or in any case have a permeability no greater than 1×10^{-5} cm/sec (§258.60[a][1]) (see Appendix B). There is a specific option for alternative cover designs for Subtitle D landfills, allowing the director of an approved state to approve an alternative final cover design that includes an infiltration layer that achieves an equivalent reduction in infiltration (§258.60[b][1]).

The goal of minimizing infiltration is readily achievable by alternative cover designs through processes other than reduced permeability layers (see Section 3.2.4). However, because these covers do not meet the specific permeability stipulations under RCRA, innovative covers are often rejected. In order to gain approval of alternative covers that control infiltration of water into the waste materials by processes other than controlling permeability, it will be necessary to review specific state regulations and to work with the regulators to determine available regulatory options.

In 1993, EPA introduced the concept of the corrective action management unit (CAMU). This modification of RCRA was intended to reduce or eliminate certain waste management requirements of the Subtitle C regulations that, when applied to remediation wastes, impeded the ability of EPA to select and implement reliable, protective, and cost-effective remedies. The practical effect of a CAMU is to allow consolidation of wastes from more than one landfill into one centralized landfill without triggering the RCRA rules regarding generation and disposal of HW.

Adoption of this rule by the states is varied. The CAMU concept is important for closure bases with multiple landfills, especially if some interpretations of RCRA regulations impact intended land reuse options. If any of the fill components of these landfills are deemed to be HW, consolidation of these landfills would be precluded. However, by designating the landfills collectively as a CAMU, it is possible to consolidate the wastes into one landfill away from the reuse area. The design of the closure system for the consolidated landfill is only required to be protective of human health and the environment.

2.1.2 CERCLA Landfill Closure Overview

Most Air Force base cleanups are carried out under CERCLA (commonly referred to as Superfund) criteria and regulations regardless of whether the site is on the National Priorities List (NPL). CERCLA establishes no specific cleanup standards or methods. Instead, CERCLA reaches out to all the other environmental, health, and/or facility siting regulations as ARARs. For landfill remediation projects, RCRA is the most significant source of ARARs. However, RCRA is intended to regulate the closure of operating landfills and is ill suited to the case of landfills that have received no waste for decades.

The implementation of alternative landfill covers under CERCLA depends on the ARAR determination for a particular site. If RCRA is found to be applicable to a cleanup, then the RCRA limitations and procedures discussed above must still be followed. The *Decision Tool for Landfill Remediation* [44] provides guidance on landfill regulations and the decisions required during the landfill closure process. Under RCRA, the appropriateness of Subtitle C requirements should be scrutinized closely at Air Force landfills containing only minor hazardous waste constituents. (The RPM is cautioned against conducting exploratory investigations in the fill unless there is substantial prior evidence to indicate that significant "hotspots" of hazardous waste exist—see Section 5.4.) The application of RCRA Subtitle C requirements by regulators makes the use of alternative cover technologies difficult, and in some cases, these requirements are not justified. The result may be a significant cost penalty for applying a RCRA cover when it is not justified on the basis of risk to human health or the environment. In this context, the RPM should remember that most municipal landfills contain small amounts of hazardous constituents that are derived from normal household waste and that the presence of hazardous waste constituents does not necessarily indicate that hazardous wastes were disposed of at a landfill.

The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) [20] is the implementing rule for CERCLA and addresses selection of an alternative remedy. Section 300.430(f)(1)(ii)(C) states "*An alternative that does not meet an ARAR under federal environmental or state environmental or facility siting laws may be selected under the following circumstances: … (4) The alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach*."

The NCP defines nine specific criteria, in three categories, for the evaluation and selection of a remedy:

Threshold Criteria
1. Overall protection of human health and the environment
2. Compliance with ARARs
Balancing Criteria
3. Long-term effectiveness and permanence
4. Reduction of toxicity, mobility, or volume through treatment
5. Short-term effectiveness
6. Implementability
7. Cost
Modifying Criteria
8. State acceptance
9. Community acceptance

The first two criteria, considered threshold criteria, are related to statutory requirements that potential alternatives must satisfy to be eligible for selection. Criteria 3 through 7, the balancing criteria, are considered during the detailed analysis to compare technical merits. The last two criteria, the modifying criteria, may be formally addressed after the public comment period.

All remedies are compared against these nine criteria to determine the best overall remedy selection. It may be difficult for innovative technologies to meet some of these criteria. Criterion 2, Compliance with ARARs, cannot be met if RCRA is used and strictly interpreted as the source of ARARs because RCRA specifies fixed values for the permeability of the cover barrier layer that may not be appropriate or technically necessary for cover designs that use a mechanism other than a barrier to minimize infiltration. In these cases, CERCLA provides a means to demonstrate that an innovative technology meets the performance requirements. Criterion 3, long-term effectiveness and permanence, must be demonstrated to apply an innovative technology. Criterion 6, implementability, may present a perception problem because the innovative technology is new. Criteria 8 and 9, state and community acceptance, may also present perception problems because the innovative technology is new.

Regulatory, technical, and acceptance issues must all be addressed in selecting and implementing an alternative technology. The ability of an Air Force RPM to gain consensus and final approval of an innovative landfill cover requires technical, regulatory, and community-relations expertise. The RPM and his team must be capable of laying the groundwork for an innovative technology and following the remedy selection process through its long, and sometimes arduous, path.

The extent of effort necessary to gain approval of an alternative cover at a particular landfill is discussed below in Section 2.4—Latitude and Process for Alternative Technology—and in Section 2.5—General Approach for the Acceptance and Installation of an Innovative Cover. An Air Force RPM is faced with significant and often conflicting urgency in selecting and implementing a remedy to meet the obligations of DOD guidance, Federal Facility Agreement schedules, and Base Closure deadlines. The opportunity to save significant costs—potentially millions of dollars at a single site—may often be overtaken by these pressures. The reward lies in achieving an innovative remediation that addresses all site risks at considerable savings. Each successful implementation of an innovative technology will pave the way for future applications of that technology.

2.2 State Regulation Framework

State regulations are important to the remediation of any site because they often are the controlling regulations. Specific federal EPA rules and regulations are discussed because they form the framework for all of the state regulations and because understanding EPA regulations provides a solid foundation for understanding regulations of individual states. Selected information is presented in the following sections for existing California and proposed Texas regulations that provide useful direction to Air Force personnel working in other states. The discussion of the proposed Texas regulatory framework is of particular interest because Texas is proposing major changes that have the potential to make innovation somewhat easier in the future. Other states may provide similar opportunities for applying innovative technologies. The RPM should check the applicable state regulations.

2.2.1 Proposed Texas Risk Reduction Program

Texas aggressively modified its laws governing the remediation and closure of contaminated sites in 1999. A new regulation, known as the Texas Risk Reduction Program (TRRP) rule, was adopted and made effective on 23 September 1999. The TRRP rule establishes a uniform set of risk-based performance-oriented technical standards to guide response actions at affected properties. The adoption of this rule puts Texas at the national forefront of remedial environmental legislation. Appendix C contains excerpts from this rule. The complete text of the rule can be found on the Internet at the following address:

http://www.tnrcc.state.tx.us/oprd/rules

The TRRP rule allows two levels of closure: Remedy Standard A and Remedy Standard B. Remedy Standard A requires removal or treatment of all contaminants in all media to achieve a risk-based cleanup standard without the use of any physical migration or exposure controls. Remedy Standard B achieves the same level of protection, but contaminants will be allowed to remain at concentrations above the cleanup standard when the associated risks can be addressed by physical migration or exposure controls. The risk-based cleanup standards, or protective concentration limits, are established for each media by back-calculating from each pathway and receptor subject to acceptable risk-based exposure limits. Residential and industrial land uses are allowed for both standards.

The TRRP rule allows for a cost-effective remedy selection that addresses the risks at a particular site. The rule defines a "functioning cap" as a low permeability layer or other approved cover meeting its design specifications to minimize water infiltration and chemical of concern (COC) migration, to prevent ecological or human receptor exposure to COCs, and whose design requirements are routinely maintained. Alternative landfill covers clearly meet these requirements for a "functioning cap." The promulgation of the TRRP rule and the application of a technically based remedial process make significant improvements in cost-effective protection of human health and the environment.

2.2.2 California Landfill Closure Regulations

The California Integrated Waste Management Act and Solid Waste Disposal Regulatory Reform Act of 1993, Section 40000 et seq. of the Public Resources Code (PRC), places the authority for waste management in the California Integrated Waste Management Board (CIWMB), State Water Resources Control Board (SWRCB) and the local enforcement agencies (LEAs). This act effectively integrated the functions of several agencies into the CIWMB and LEAs, with ancillary assistance from SWRCB and other appropriate state and regional agencies as discussed below and in the regulations.

California law is based upon federal RCRA and other statutes, as are the laws in all of the other states. These laws generally are based on the barrier-type covers that constituted current technology when the federal rules were written; they are not reviewed here again. This discussion and the material included in Appendix D focus instead on rules for landfill covers and the opportunities offered by the California laws, rules and regulations for use of innovative concepts in landfill covers.

The specific solid waste (SW) landfill cover requirements are found in California's Solid Waste Closure law [§21090 SWRCB, Closure and Post-Closure Maintenance Requirements for Solid Waste Landfills (C15: §2581 // T14: §17777, §17779)]. These requirements call for the installation of a "Low-Hydraulic-Conductivity Layer" compacted to attain a hydraulic conductivity of either $1x10^{-6}$ cm/sec (1 foot/year) or less, or equal to the hydraulic conductivity of any bottom-liner system or underlying natural geologic materials, whichever is less permeable, or another design that provides a correspondingly low through-flow rate throughout the post-closure maintenance period.

The SWRCB can allow any alternative final cover design that the Board finds will continue to isolate the waste in the unit from the effects of precipitation and irrigation waters at least as well as would a final cover built in accordance with applicable prescriptive standards. This so-called "low through-flow rate" is attainable by alternative cover designs, which are therefore permissible under the law.

Additional general closure flexibility is provided in SWRCB, General Requirements. (C15: §2510) 20080(4)(b). This regulation allows for alternative solutions to SWRCB regulations where the prescriptive remedy is infeasible and the alternative meets the requisite goals and performs an equivalent function to the prescriptive remedy. In order to prove infeasibility, the discharger must either show that there is an unreasonable burden and substantially greater cost than the alternative or that the prescriptive remedy will not meet the requisite goals of this regulation.

2.3 EPA Directives & Other Aids to Implement Innovative Technologies

EPA, DOD, and the states support multiple programs, research efforts, and regulatory initiatives to develop and implement innovative technologies. EPA has developed guidance, policy, directives, and agreements on innovative technologies. A common theme throughout these efforts is to gain acceptance and approval for the implementation of innovative technologies and to overcome regulatory and technical conservatism. Resources available to the RPM support the use of innovative technologies, particularly alternative covers, and the following subsections provide a starting point for the selection of alternative landfill covers. Additionally, Appendix E provides a listing of Internet sites that have up-to-date information on the application of innovative landfill technologies.

2.3.1 Promotion of Innovative Technologies in Waste Management Programs

EPA's Office of Solid Waste and Emergency Response (OSWER) Policy Directive 9380.0-25 defines EPA's support of innovative technologies, and it expresses EPA's frustration with the difficulty of getting innovative technologies approved and implemented in the field [72]. In the second paragraph of the Directive, EPA OSWER states: *"A recent analysis of Superfund Feasibility Studies found cases where innovative technologies were eliminated from consideration because they required testing to determine their applicability at a particular site. Promising new technologies should not be eliminated from consideration solely because of uncertainties in their performance and cost, particularly when a timely treatability study could resolve those uncertainties."*

In Directive Section (4), entitled Streamline RCRA Permits and Orders for Innovative Treatment Technology Development and Use, EPA writes, *"We need to work more as team members, rather than traditional regulators, to coordinate with EPA laboratories, other federal agencies, states and the private sector in pursuit of our common interest of furthering new processes."* The Directive continues in section (4)(a), entitled Avoid Unnecessary Regulatory Control, *"When considering new technology applications, we need to ask ourselves whether prior assurance that cleanup standards will be met is necessary. For treatability studies and demonstration projects, seeking assurance of success as a precondition to testing makes little sense since this is the purpose of the investigation itself."*

Directive Section (6), entitled Utilize Federal Facilities as Sites for Conducting Technology Development and Demonstrations, documents EPA's commitment to promote the use of federal facilities as demonstration and testing centers for innovative environmental technologies. *"Federal facilities offer unique opportunities for the development and application of both field site characterization and cleanup technologies. Regions are encouraged to work with states as co-regulators to ensure acceptance and with other federal agencies to promote testing and use of new approaches. Cooperative efforts are needed to develop permit conditions which do not unreasonably restrict technology demonstrations at federal facilities."*

Overall, this is a critical directive because it states EPA's explicit support for innovative technologies. However, EPA acknowledges that the regulatory environment at both the federal and state level is an ongoing impediment to the selection and implementation of innovative technologies. The Directive gives some helpful information to the RPM on how to build a consensus for a particular technology at their site.

2.3.2 EPA Policy for Innovative Environmental Technologies at Federal Facilities

Carol Browner, EPA Administrator states in *EPA Policy for Innovative Environmental Technologies at Federal Facilities* (Figure 1) that "EPA will … work with the Federal agencies and interested stakeholders to overcome the regulatory and institutional challenges affecting the application and commercialization of environmental technologies." The Administrator could not have stated more strongly her support of using innovative technologies at federal facilities.

2.3.3 Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills

Presumptive remedies are preferred technologies for common categories of sites. They are based on historical patterns of remedy selection and the EPA's scientific and engineering evaluation of performance data on selected technologies. By streamlining site investigation and accelerating the remedy selection process, presumptive remedies are expected to ensure the consistent selection of remedial actions and reduce the cost and time required to clean up similar sites. Presumptive remedies are expected to be used at all appropriate sites. Site-specific circumstances dictate whether a presumptive remedy is appropriate at a given site.

Presumptive remedies employ a streamlined risk assessment. A streamlined risk assessment for a municipal landfill focuses on the most obvious problems at the landfill (e.g., groundwater contamination, leachate, landfill contents, and landfill gases) to provide a clear and quick indication that remedial action is warranted at the landfill. The risk assessment is streamlined because it does not provide a fully developed, quantitative assessment of the risks associated with all contaminants, exposure pathways, and potentially exposed receptors. The streamlined risk assessment identifies exposure pathways in a conceptual site model, explains how the presumptive remedy addresses each pathway, and focuses on risk assessment for any pathways not addressed by the presumptive remedy.

EPA established source containment as the presumptive remedy for municipal landfill sites regulated under the *Presumptive Remedy for CERCLA Municipal Landfill Sites* [70]. The municipal landfill presumptive remedy should also be applied to all appropriate military landfills using the guidance in *Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills* [71]. This directive provides a step-by-step approach to determining when a specific military landfill is an appropriate site for application of the containment presumptive remedy. It identifies the characteristics of municipal landfills that are relevant to the applicability of the presumptive remedy, addresses characteristics specific to military landfills, outlines an approach to determining whether the presumptive remedy applies to a given military landfill, and discusses administrative record documentation requirements. Figure 1 of the *Decision Tool* [44], described in Section 5.1.2, illustrates the decision process to determine if the EPA's presumptive remedy selection procedure for landfill closures is appropriate for an individual military landfill.

2.3.4 Joint EPA/State Draft Agreement to Pursue Regulatory Innovation

This draft agreement [73] was prepared jointly by the EPA and Environmental Council of the States to promote and implement future regulatory innovation efforts. The agreement will encourage and facilitate the exploration of ideas that are potentially more cost-effective or have a better environmental impact. Figure 2 shows an excerpt from the draft agreement, still in

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460
AUG 19 1994

THE ADMINISTRATOR

EPA Policy for Innovative Environmental Technologies at Federal Facilities

The Federal government has a responsibility to become a leader in promoting and developing technological solutions for environmental protection. Due to the magnitude of the Federal Facilities cleanup and compliance challenge and our commitment to catalyze technological solutions for environmental needs, Federal facilities offer unique opportunities for the development and application of innovative technologies and approaches to pollution prevention, source control, site investigation, and remediation.

Federal facilities offer unique opportunities for collaborative efforts on technology innovation involving EPA, other Federal departments and agencies, and the private sector. These opportunities have become even more apparent recently as the Departments of Defense and Energy shift missions and literally "open their doors" to allow both public and private groups to take advantage of their technological capabilities for environmental purposes.

Collaboration among the Federal government, states, the public, and industry to develop technological solutions to environmental problems will address environmental needs while creating jobs and spurring economic development. EPA will also work with the Federal agencies and interested stakeholders to overcome the regulatory and institutional challenges affecting the application and commercialization of environmental technologies.

EPA is committed to actively promoting and facilitating the use of federal facilities as demonstration and testing centers for the development of innovative environmental technologies. In addition, I encourage the incorporation of innovative technology conditions in appropriate EPA/Federal Agency clean-up and compliance agreements. Such technology conditions, when carefully crafted, can provide encouragement for innovation while still holding the Federal agency and regulators accountable for environmental protection.

Therefore, today I am announcing this policy to promote and support the use of Federal facilities as demonstration and test centers for the development and application of innovative environmental technologies.

To implement this policy, EPA shall:

Actively seek state, community and other stakeholder support and involvement in Agency policies that affect environmental technologies and in Federal facility technology development and demonstration projects;

Focus on private sector involvement to 1) enhance technology commercialization, job development, and economic growth; and 2) highlight real application and early field work for current clean-ups and the prevention of future pollution;

Seek opportunities to use innovative technology to reduce or eliminate waste or pollution;

Increase cooperative efforts with the federal and private sectors to determine how technology may factor into remedy selection;

Exercise leadership in the development of a coordinated interagency strategy implementing the concept of utilizing federal facilities as technology development and demonstration centers for pollution prevention, control and site investigation/clean-up; and

Provide direction by sponsoring informational and policy meetings on innovative technologies this year and in the future to serve as the basis for the development of this interagency strategy.

Through environmental improvement, economic growth and international export, EPA will continue to explore and define its interagency role in coordinating leadership, development and implementation of innovative environmental technologies. I encourage your strong support for this concept as it continues to evolve and take shape in the future.

Carol M. Browner

Figure 1. EPA's Innovative Technology Policy

draft status, which powerfully reinforces the commitment by the EPA and the states to find innovative regulatory solutions and to avoid being constrained by outdated or overly restrictive regulations. The draft agreement emphasizes that regulatory innovation activity should start with the states, because the states are generally delegated RCRA authority and they need to support and pursue regulatory relief.

2.3.5 The Federal Remediation Technologies Roundtable

The Federal Remediation Technologies Roundtable [21] was established in 1990 as an interagency committee to exchange information and to provide a forum for joint action regarding the development and demonstration of innovative technologies for hazardous waste remediation. Roundtable member agencies expect to complete many site remediation projects in the near future, and recognize the importance of providing expedited access to federal resources for technology developers and others interested in innovative technology development. Table 1 provides a list that the Roundtable compiled of active federal government programs promoting the development and implementation of innovative technologies.

EPA analyzed market trends for innovative technologies and determined that at least 30 percent of the Superfund sites will implement innovative technologies for some degree of source control. Alternative landfill covers should be a significant part of the innovative technology used.

The number of federal government programs involved in the development of innovative technologies is impressive. Each of these programs has identified target technology gaps for the sites within their agency's responsibility. Bringing these technologies through development, testing, and acceptance is a challenge faced by each agency. DOD's Environmental Security Technology Certification Program summarizes the challenge in their statement, "*Successful demonstration facilitates the acceptance of innovative technologies by users and the regulatory community.*"

2.4 Latitude and Process for Alternative Technology

Selection of innovative technologies for use at sites in the CERCLA and RCRA cleanup programs is difficult because there is an inherent conflict between stringent regulatory interpretation of cleanup requirements and the application of innovative technologies. EPA is aware of this conflict and has attempted to provide its regulators with significant support in the selection and application of innovative technologies. The development and application of innovative technologies has been identified as the weak link in the remediation process since the earliest days of the CERCLA and RCRA cleanup programs. Congress acknowledged this issue in the Superfund Amendments and Reauthorization Act of 1986 (SARA)[1]: "*The Administrator is authorized and directed to carry out a program of research, evaluation, testing, development, and demonstration of alternative or innovative treatment technologies …which may be utilized in response actions to achieve more permanent protection of human health and welfare and the environment*."

[1] Public Law 96-510.

State and EPA agree that the following principles should guide us as we develop, test, and implement regulatory innovations:

Experimentation: Innovation involves change, new ideas, experimentation, and some risk of failure. Experiments that will help us achieve environmental goals in better ways are worth pursuing when success is clearly defined, costs are reasonable, and environmental and public health protections are maintained.

Environmental Performance: Innovations must seek more efficient and/or effective ways to achieve our environmental and programmatic goals, with the objective of achieving a cleaner, healthier environment and promoting sustainable ecosystems.

Smarter Approaches: To reinvent environmental regulation, regulators must be willing to change the way we traditionally look at environmental problems and be receptive to innovative, common sense approaches.

Stakeholder Involvement: Stakeholders must have an opportunity for meaningful involvement in the design and evaluation of innovations. Stakeholders may include other state/local government agencies, the regulated community, citizen organizations, environmental groups, and others. The opportunities for stakeholder involvement should be appropriate to the type and complexity of the innovation proposal.

Measuring and Verifying Results: Innovations must be based on agreed-upon goals and objectives with results that can be reliably measured in order to enable regulators and stakeholders to monitor progress, analyze results, and respond appropriately.

Accountability/Enforcement: For innovations that can be implemented within the current regulatory framework, current systems of accountability and mechanisms of enforcement remain in place. For innovations that involve some degree of regulatory flexibility, innovators must be accountable to the public, both for alternative regulatory requirements that replace existing regulations and for meeting commitments that go beyond compliance with current requirements. Regulators will reserve full enforcement authority to ensure compliance with alternative regulatory requirements, and must be willing to explore new approaches to ensure accountability for beyond-compliance commitments.

State-EPA Partnership: The states and EPA will promote innovations at all levels to increase the efficiency and effectiveness of environmental programs. We must work together in the design, testing, evaluation and implementation of innovative ideas and programs, utilizing each other's strengths to full advantage.

EPA agrees to establish a process that ensures timely review and decision-making on state innovation proposals based on implementation of the above seven principles. The states agree to consult early with EPA, to develop proposals consistent with the above principles, and to involve stakeholders. EPA and the states agree on the need for a clearinghouse of regulatory innovations so that promising ideas can be shared across state lines and within EPA.

Figure 2. Excerpt from Joint EPA/State Draft Agreement

Table 1. Federal Site Remediation Technology Development Assistance Programs

Interagency R&D Assistance Programs

- National Environmental Technology Test Sites Program (NETTS)
- Rapid Commercialization Initiative (RCI)
- Remediation Technologies Development Forum (RTDF)
- Small Business Innovative Research Program (SBIR)
- Strategic Environmental Research and Development Program (SERDP)

U.S. Department of Defense R&D Assistance Programs

- Air Force Center for Environmental Excellence/Innovative Technology Program
- Environmental Security Technology Certification Program (ESTCP)
- Naval Environmental Leadership Program (NELP)

U.S. Department of Energy R&D Assistance Programs

- Industry and University Programs Area
- Program Research & Development Announcements (PRDAs)
- Research Opportunity Announcements (ROAs)
- Small Business Technology Transfer Pilot Program

U.S. Environmental Protection Agency R&D Assistance Programs

- Environmental Technology Initiative (ETI)
- Environmental Technology Verification Program (ETV)
- National Center for Environmental Research and Quality Assurance (NCERQA)
- Superfund Innovative Technology Evaluation Program (SITE)

Innovative technologies offer significant promise of reducing the huge cost burden of remediation. The greatest strides in these cost savings technologies are being made in the use of biological processes to control migration or to treat various wastes. Particularly important are *in situ* technologies that use biological, physical, and chemical processes. For example, the Air Force was a compelling force in the development and acceptance of bioventing and natural attenuation. As a result, the underground petroleum cleanup program costs have been reduced by billions of dollars. The development and use of other biological systems is expanding to the treatment of air, wastewater, soil, sediments, groundwater, landfill covers, and the waste material itself. The battle for implementing these technologies continues to be waged at individual sites.

EPA has laid extensive groundwork in the application of innovative technologies. The challenge comes with the approval and fielding of a particular technology at a specific site. Approval of innovative landfill covers is often presented as a five-step approach [11]. However, an essential first step is the establishment of performance requirements in cooperation with the regulatory bodies and with concurrence by the public. Thus, there are actually six steps in gaining acceptance of innovative technology, listed as follows with the added first step italicized for emphasis:

1. *Landfill owner and regulators establish performance requirements.*
2. Review all available data to determine the appropriateness of an alternative cover.

3. Meet with regulating agency to identify concerns, and judge feasibility.
4. Develop potential alternative designs and cost estimates and compare results.
5. Laboratory test and computer model proposed designs.
6. Prepare report.

This process is applicable at landfills completing operation and ready to undergo closure. However, at federal facilities, there are few landfills at which a simple, straightforward, innovative technology acceptance process is possible. In general, Air Force landfills have been unused for years or decades, and these landfills have been studied through various remedial investigations and feasibility studies. Often landfill closure schedules are included in CERCLA Federal Facility Agreements or RCRA Permits. The relationship of a particular Air Force base with its state and federal regulators and with the public is based on nearly two decades of remedial programs. The introduction and acceptance of an alternative closure at one landfill is not a simple singular matter; instead, it must be seen in the context of the current base remediation program.

Realistically, the selection and approval of an alternative cover at a particular Air Force landfill is a lengthy process. Each of the sequential steps described above must be addressed, but some issues must be dealt with concurrently and/or iteratively. Approval of an alternative landfill cover may require additional monitoring, and the regulations may require specific stipulations before approving the proposed technology. The Air Force RPM should coordinate input from various Air Force experts from their command, their service center, and contractors. They must then develop a unified presentation of the particulars of a proposed technology and provide reasons for application of this technology at a particular site. The technology must be shown to meet the performance requirements for the particular application. The resulting benefits to the Air Force may include cost advantages (in construction and/or long-term operation and maintenance), schedule improvement, or greater risk reduction.

Alternative landfill cover technology may require relief from some regulations or ARARs. Some RCRA regulations are so specific that the performance requirement of a final cover is focused on the permeability of specific layers. Innovative covers may not be strictly equivalent to conventional covers because they contain no impermeable layers. However, innovative landfill cover designs that use a different mechanism to control water movement may meet the cover performance requirements. Equivalency between alternative and conventional covers may imply that a non-barrier is equal in construction to a barrier cover. This is obviously not possible. However, equivalency of performance requirements between conventional and innovative technology not only is possible but is also a reasonable requirement and an understandable basis for acceptance.

The RTDF Phytoremediation of Organics Action Team, Alternative Cover Subgroup, an EPA-sponsored forum with participation from EPA, states, universities, the Air Force, and industry is a major proponent of innovative or alternative landfill cover technologies. The group has identified several key issues related to the acceptance of alternative covers. The following is abstracted from various discussions and meetings of the RTDF and posted on their web page (www.rtdf.org). None of the following information reflects the Air Force's, EPA's, or any other member organizations' formal stand on a particular issue. Key issues identified by the Forum related to the acceptance of alternative covers include the following:

- **Public Acceptance:** Public perception of protectiveness is dependent on many factors. The specific technical arguments are often not well communicated and the perceived emphasis on cost savings can create doubt regarding protection of public health.
- **Regulatory Impediments:** Permit writers need to be assured that the alternative cover provides the same level of protection and risk reduction as a traditional cover. Regulatory acceptance of alternatives will be based on technical demonstration and evaluation.
- **Equivalency/Performance:** Current RCRA design guidance is based on the hydraulic permeability of specific layers in the final cover. Alternative covers generally control water movement through other mechanisms. Long-term performance and maintenance requirements are also important performance issues that must be addressed and demonstrated. The issue of equivalency and long-term performance may ultimately require formal regulatory relief to ensure widespread acceptance and ultimately to allow proven alternative covers to assume their role as accepted alternatives.
- **Risk Issues (Human health and environmental):** The driving force of all landfill covers is the protection of human health and the environment. Alternative covers must provide protection that is comparable to conventional covers in controlling the source, migration, and exposure to contaminants.
- **Modeling:** The long-accepted standard model for landfill cover performance is the Hydrologic Evaluation of Landfill Performance (HELP) model. HELP was developed for conventional barrier cover designs and does not consider the full complexities of climate, plant growth, and evapotranspiration (ET) needed to design vegetative soil covers. There are other more sophisticated models that handle each of these factors with greater sophistication; however, there is neither widespread familiarity nor acceptance of these models among the regulators.
- **Design Guidance:** The design of alternative covers has to date been an isolated activity directed at specific sites. There is no general design guidance available for alternative covers. This lack of generally accepted design criteria is a time-consuming impediment in every approval attempt.
- **Monitoring Methods:** Alternative covers may be subjected to additional monitoring requirements to determine specific performance variables. The gathering of this performance data is crucial to the proof of the particular alternative cover concept, as well as to calibrating models and developing general design criteria. These requirements may initially increase costs until the design has been proven, but for landfills closed at a later date, costs could be much less.

2.5 General Approach for the Acceptance and Installation of an Innovative Cover

The selection of an innovative cover at a single landfill can result in performance equal to a conventional cover while saving millions of dollars (see Section 3.2 for a discussion of innovative landfill covers). The knowledge base and choices of alternative covers are expanding rapidly; therefore, previously chosen cover remedies for a landfill undergoing closure should be reexamined to determine if an alternative cover is appropriate. The earlier in the process of remedy selection that changes are made, the easier it will be to address the technical, regulatory, and acceptance issues. However, CERCLA permits modification of a

Record of Decision (ROD) at any time before the completion of the Remedial Design [20]. Thus, the introduction of an innovative technology may still be appropriate even when the remedial design is under way.

The following 12-step process is applicable to the closure of all Air Force landfills. The process may be iterative, and each step may have significantly different emphasis at a particular base or for a particular landfill.

1. Determine risks at the specific landfill.
2. Determine site-specific performance requirements in concert with the regulators.
3. Select the most appropriate conventional or alternative technologies and gather technical performance data, modeling, and field demonstration studies.
4. Present a unified Air Force proposal to the regulators for use of the selected technologies based upon the performance requirements.
5. Elicit wide regulatory participation, including regulatory managers, EPA headquarters, and EPA laboratories.
6. Aggressively challenge regulatory interpretation of ARARs or other limitations on alternative technology selection.
7. Present the proposed technology to the Remedial Advisory Board and the public, preferably with regulatory buy-in.
8. Complete any required modeling, design criteria, and/or feasibility testing.
9. Conduct peer reviews of the decision process and remediation design
10. Formally document the selection of the technologies in the decision document (ROD).
11. Complete the design and monitoring plan.
12. Construct all of the remediation components and gather monitoring and performance data. Disseminate the information within the Air Force to build support and acceptance for each technology alternative.

The increased protectiveness and potential cost savings offered by appropriate alternative covers demands that each Air Force RPM review these options for each closing landfill. The successful demonstration of alternative covers at Air Force landfills will ultimately translate into savings of hundreds of millions of dollars to taxpayers and the private sector [43].

2.6 Risk-Based/Performance-Based Landfill Evaluation

The preceding discussions of regulations and the selection of appropriate landfill cover options illustrates the limits imposed on making purely "technical" decisions to select new technologies and remedial options. Risk-Based/Performance-Based (RB/PB) landfill evaluation introduces a process that may minimize or eliminate regulatory prejudices for a particular technology. There is already a strong regulatory basis for this process in the NCP (i.e., CERCLA) and in the proposed TRRP rule; however, the successful use of the process discussed here has been limited. Air Force RPMs can use the resources identified in Sections 2.1 through 2.5 of this report to successfully follow this approach in their landfill closure decisions.

An RB/PB landfill evaluation is a technically based approach to select protective remedial options based on the specific conditions at a landfill. Using an RB/PB evaluation will allow the landfill owner to determine the specific technical performance requirements necessary to address all risks at a landfill. After these requirements are determined and accepted by the public and regulatory community, any particular landfill remediation scenario that meets them, including alternative or innovative covers, can be selected.

The RB/PB landfill evaluation process follows four well-defined steps used in environmental risk assessments:

1. **Identification of Releases**: Based on known waste materials and environmental sampling, determine the releases associated with a particular landfill, including the following:
   - Surface materials
   - Gas generation
   - Leachate production
   - Groundwater and surface water contamination
2. **Exposure Assessment**: Determine the exposure pathways to potential receptors, including the following:
   - Direct contact
   - Airborne contamination
   - Surface water or groundwater contamination
3. **Risk Assessment**: Determine the risks associated with each source–pathway–receptor combination.
4. **Performance Requirements**: Determine the specific performance requirements of each action that must be taken to address the risks identified, including the following:
   - Cover requirements to eliminate direct contact
   - Limitation of infiltration to control leachate generation
   - Collection and/or treatment of gas, if necessary
   - Control of groundwater contamination
   - No-further-action if no significant risks were identified

After a performance requirement has been established for a particular remedial action, any remedial alternative meeting that requirement can be selected and applied at that landfill. This process eliminates the need to follow the classical ARARs approach to determine closure requirements, and it allows the owner to select the most technically sound and cost-effective alternative to address the risk at a particular landfill. The selection of performance requirements is discussed in Section 5.7.

3 Containment Technology

This section describes the components of a typical landfill remediation. Much of the discussion will focus on surface covers because they are the most frequently required, the most complex, and typically the most costly component of a landfill remediation. Other components—including landfill gas collection and disposal, leachate collection and treatment, hydraulic control of groundwater flow at the site, and remediation of contaminated groundwater and surface water—are discussed at the conclusion of this section.

Final landfill covers (sometimes called caps) are placed during remediation and remain in place as an essential part of the waste containment system. In the context of remediation, the word "cover" is understood to refer to a final landfill cover. Over the past several decades, technologies have developed and advanced to enable the effective covering of landfills in accordance with environmental goals. At the same time, the process has become an expensive proposition and one largely driven by regulation. Ironically, regulations are sometimes blindly followed to the neglect of innovative technologies that can provide an environmentally responsible solution at considerable cost savings.

This section provides a review of the types of landfill remediation components that are available today and identifies the important factors that must be considered in selecting and designing them. Section 3.1 discusses the site characteristics that play a dominant role in selecting an appropriate landfill cover. Section 3.2 describes various technical approaches for achieving the objectives of a landfill cover. Innovative cover designs that use mechanisms other than a physical barrier to minimize water infiltration are discussed in Section 3.3. Section 3.4 discusses other components—such as leachate collection and treatment—that are part of the complete landfill remediation.

3.1 Site-Specific Aspects of Landfill Cover Selection and Design

The integration of containment components into design elements is dependent on specific site characteristics. The site characteristics that have a dominant influence on choosing an appropriate final cover include climate, soils, landfill characteristics, hydrogeology, gas production, seismic environment, and reuse of landfill areas. Each of these factors is discussed below.

3.1.1 Climate

Precipitation (rain, snow, and sleet), solar radiation, temperature, and wind are the main climatic factors that affect landfill covers. Precipitation levels, of course, have a direct bearing on infiltration of water into the cover and, potentially, into the buried waste. Climatic factors also strongly influence ET, which acts to reduce infiltration. Degradation rates of biodegradable wastes are affected by climatic variables through the effects on moisture content and temperature. Erosion of the cover soil is directly affected by factors such as precipitation and wind.

It is important to note that the commonly reported annual or monthly averages of climatic variables do not provide sufficient information by which to evaluate a site. Seasonal and daily variations are important considerations. For example, if precipitation is seasonally distributed such that the majority falls during the period when vegetation is dormant, the potential for infiltration through the cover is much greater than if the precipitation falls mainly during periods of active growth. In some areas of the United States, snowpack accumulates during the winter months and then melts during a relatively short period in the spring. At this time, ET may be low (increasing the potential for infiltration) and the ground still frozen (decreasing the potential for infiltration). Both circumstances will impact infiltration rates, and the analysis of these factors may be complex.

Beyond macro-climatic effects, there is also a strong influence from daily or even hourly patterns. A series of precipitation events that saturate the soil in a few days will result in greater infiltration potential than the same total amount of precipitation spread over a period of weeks. The antecedent moisture condition is just one factor that illustrates the complexity of climatic interactions that have to be considered in evaluating potential landfill covers. In addition to the general conditions, the concept of a "critical event" (one that produces extreme conditions) must be taken into account. An example of such a critical event would be an extended period of rain following snowmelt that coincides with a period when vegetation is dormant. The occurrence of this combination of conditions may take place only once in several decades, yet it would determine the design requirements that must be met.

3.1.2 Soils

The availability of appropriate local soils is an important consideration in any landfill design. Local soils are often needed for the surface and foundation layers of the cover, as well as for a compacted barrier layer in conventional designs. Nearly any local soil may be used for the foundation layer. The surface layer soils, however, must be suitable for supporting the surface vegetation. Major factors determining effectiveness of the soil for supporting vegetation are grain size, soil pH, and cation exchange capacity (CEC). An adequate supply of nutrients to support vigorous plant growth is also required but can be achieved by using soil amendments if the CEC is high enough.

The U.S. Department of Agriculture (USDA) soil textural classification guide is shown in Figure 3. Generally, loam soils make excellent cover material for landfills. Soils made up largely of sand tend to dry out rapidly because they have low water-holding capacity, and they tend to lose nutrients by leaching. Differences in available soil type also influence the selections of vegetation and mulch. Although soil can be classified by visual inspection, the determination of soil type and soil properties should be based on appropriate soil testing. Soils should be classified and described for each site by a professional soil scientist or soil classifier.

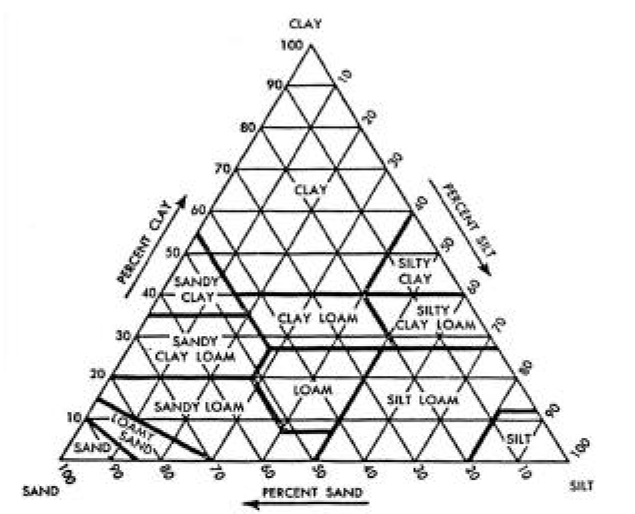

Figure 3. USDA Textural Classification of Soils

A landfill cover that relies on a conventional barrier system often incorporates a compacted clay layer (CCL) into the design. The availability of local soil that has the necessary properties to compose this layer is a critical cost factor in selecting the appropriate design. If soils with the required properties are not locally available, the cost of importing soil from a distance or augmenting local soils to obtain specific physical properties will be significant. Installation of a geosynthetic clay layer (see Section 3.2.1.3) may also be a cost-effective alternative to supplement local soils if clay soils are not available locally.

Accurate information about soils on and near a site is particularly valuable for the evaluation of alternative covers. The design of ET covers, for example, is heavily dependent upon the specific characteristics of soils used. Water-holding capacity, in particular, is important, and the cover will not be practical unless sufficient soils with the appropriate characteristics are available within a short distance of the site.

3.1.3 Landfill Characteristics

The operating history, wastes, and physical construction of the landfill will all affect the remediation options that may be used. For example, some of the characteristics that affect cover design include the type of waste deposited, whether or not the landfill has a liner, the age of the landfill, whether the landfill is active or inactive, and whether or not leachate is being produced.

The type of wastes disposed of in a landfill leads to its classification as (1) municipal or sanitary (consisting of typical household wastes), (2) hazardous, (3) radioactive, or (4) mixed waste (non-radioactive mixed with radioactive). The waste classification directly impacts the cover design because of both the technical and the regulatory requirements. For example, radioactive waste requires longer-term storage and must consider the potential generation of radon gas. Air Force landfills hold primarily municipal type wastes, but many have received waste solvents, fuels, or other hazardous materials. The physical form of the waste and its chemical properties are an important consideration in selecting materials for the cover and in choosing groundwater remediation options, if needed. If the buried waste is biodegradable, production of landfill gas can be anticipated, so gas collection must be considered when designing the cover.

Although gas production in a landfill can continue for long periods, high rates occur over relatively short periods, perhaps up to ten years after the landfill becomes inactive. A recent survey found that about 86 percent of Air Force landfills have been dormant for more than 20 years [43]. Therefore, in comparison to a modern landfill that was covered immediately after filling, the final cover design for an Air Force landfill is less likely to require the expense of a gas collection system.

As a landfill ages, the degradation of the waste and the pressure of overlying materials lead to compression and settling of the waste, sometimes by as much as 33 percent [57]. The resulting subsidence of the overlying cover can cause severe problems with the cover materials including development of cracks in clay barriers, separation of geomembranes (GMs), and slope changes that adversely affect surface water drainage and erosion. Again, the fact that most Air Force landfills are older means they are less likely to sustain excessive surface subsidence that adversely impacts the finished cover.

A bottom-liner system, required for any landfill constructed today, is a significant landfill component that, if present, must be taken into consideration in any final cover design. Current RCRA regulations specify that the hydraulic conductivity of the cover must be less than or equal to that of the bottom liner. However, almost all Air Force landfills were built before the advent of the present rules requiring a liner. A recent survey indicated that only 1 of 229 U.S. Air Force landfills surveyed had a bottom liner [43]. Therefore, cover system design for the remediation of Air Force landfills typically should not be restricted by rules and regulations that are pertinent to modern RCRA landfills with liners.

3.1.4 Hydrogeology

The distance between the bottom of an unlined landfill and the water table is an important determinant of the probability that groundwater has been or may be contaminated. If the landfill has no liner but rests on highly impermeable bedrock, shale, or clay and if the depth to groundwater is great, then an older Air Force landfill poses little threat to groundwater. Therefore, the geology of the site and the lithology of geologic units between the waste and permanent groundwater are important considerations. If waste is actually in contact with groundwater, a surface cover alone cannot provide a complete remedial solution for the site. A landfill cover at such a site should be selected with extra care and integrated with the other remediation technologies being employed.

3.1.5 Gas Production

Gas production must be considered in the overall cover design. Natural decay of wastes and volatilization of wastes in landfills may produce sufficient toxic and/or explosive landfill gas to warrant gas control systems under the cover. Gas control systems may be either passive (natural flow) or active (using vacuum pumps or blowers). A cover that employs a conventional barrier layer is likely to require an expensive gas control system because the barrier will trap the gas produced, even at low rates, and may result in dangerous volumes of explosive and/or poisonous gas. Some innovative covers, such as the ET cover, contain no barriers that might collect gas. Instead, these covers allow small amounts of landfill gas to pass harmlessly through the cover soil into the atmosphere.

3.1.6 Seismic Environment

Earthquakes are a significant threat to public safety and welfare over many parts of the United States, particularly the West Coast, Alaska, parts of the Rocky Mountains and the Mississippi Valley, and selected areas of the Eastern Seaboard. The ground-shaking associated with earthquake activity can damage landfill infrastructure in many ways, including landslides on the cover slopes, rupture of geomembrane barrier layers, cracking of clay barrier layers, breakage of conduit lines (gas control and drainage systems, electrical controls, etc.), and changes in drainage slopes.

Matasovic et al. [38] studied the performance of landfill covers and liners during the six major earthquakes in California between 1969 and 1994. The performance was good to excellent at all of the landfills with the damage limited to cracking of cover soils at many sites and damage to one geosynthetic liner. However, no landfills with a geosynthetic cover have been subjected to strong ground motions. Therefore, within seismic hazard zones, landfill designs should be evaluated using site-specific seismic risk assessment criteria, and special attention to detail is warranted in the design of a composite cover with a geosynthetic membrane. Richardson and Kavazanjian [51] have written an extensive treatment of this aspect of landfill design.

3.1.7 Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection and design. However, one should not lose sight of a basic assumption about modern landfills—they are intended to be warehouses for waste material and to serve for an unknown length of time. Therefore, if the site is used as a landfill, other uses are secondary.

The very fact that human activity is expected on a final landfill cover requires that more critical attention be given to its design. Former landfill sites find new life as parks, nature areas, and bicycle paths. The anticipated use will require using compatible materials in the cover, selecting vegetation that provides the necessary cover functions and is also appropriate for the end use, and perhaps modifying the site topography.

Some apparently beneficial uses may be in conflict with primary cover purposes. For example, golf courses are usually irrigated frequently, which can result in large volumes of water moving below the root zone. Golf courses on landfill covers pose immediate problems because one of the principal objectives of a landfill cover—to minimize infiltration—probably cannot be achieved.

3.2 Conventional Landfill Covers

The final remediation of a landfill may require that several components work together to contain the waste and its byproducts of landfill gas and leachates. The complete remediation design usually includes a surface cover and may also include gas collection and disposal, leachate collection and disposal, and hydraulic control of groundwater at the site. This discussion focuses on landfill remediation components for military landfills that have distinctive characteristics affecting cover selection and design. For example, they usually have no bottom liner, may have been unused for many years, and may contain primarily municipal-type wastes.

Landfill covers are used at various times during a site's active life. At modern landfills, a thin soil cover is placed over the waste at the end of each day to control odors, prevent litter movement by wind, and keep rodents, birds, and insects out of the waste. Intermediate soil covers are often used to protect areas of an active landfill that will not be covered with additional waste or a final cover for an extended time. Intermediate covers provide the same function as daily cover and are also contoured to encourage surface runoff. McBean et al. [40] present a more complete discussion of daily and intermediate landfill covers. Landfill covers placed during remediation, sometimes referred to as final covers, remain in place as an essential part of the waste containment system.

Landfill covers provide a protective layer to isolate the underlying waste from the environment. For many landfills, the cover is the most important component of the waste containment system. The requirements for cover performance differ depending on the type of waste involved. For example, when covering a landfill containing significant quantities of radioactive materials, it is important to control even small quantities of radioactive gases. In contrast, a military landfill that has been inactive for more than 20 years and contains primarily municipal-type waste may require no gas control system within the cover.

Because a landfill cover is apt to remain in place for decades or even centuries, there are design considerations that are important to maintain its functions and ensure long cover life. Landfill covers must minimize precipitation infiltration because water that percolates through the waste may carry soluble wastes downward to groundwater, thus creating a threat to human health or the environment; an effective landfill cover can minimize this threat. Covers that meet the infiltration requirement will usually satisfy the requirement that the waste should be isolated from receptors. Depending upon site conditions, the cover may also be required to control gas that the landfill produces and to protect the barrier layers within the cover from freezing.

Nearly all landfill covers in place today are conventional, barrier-type landfill covers that have been installed in the last few decades. Compacted clay and synthetic materials are common components in these barrier-type covers. These designs, which are often accepted as presumptive remedies, place a barrier layer within the cover that is intended to prevent water from moving downward in response to the force of gravity. In effect, these covers are designed to oppose the forces of nature. Some innovative cover systems also rely upon the barrier concept, but others do not. Later sections discuss these types of innovative covers.

3.2.1 RCRA Subtitle C Covers

Conventional RCRA Subtitle C covers employ barrier technology and typically include five layers above the waste (Figure 4); some covers employ only some of these layers. The top layer consists of ***cover soil*** that supports a grass cover to provide wind and water erosion control. The second layer is a ***drainage*** layer that quickly removes any water that percolates through the cover soil; the water is stopped by the underlying barrier layer. The ***barrier*** layer consists of either a single low-permeability barrier or two or more barriers in combination. The fourth layer is the ***gas collection*** layer that is needed under the barrier to remove landfill gases before they can accumulate in harmful amounts. The bottom layer is a ***foundation*** layer of variable thickness and material. Its purpose is to separate the waste from the cover and to establish adequate surface slope to promote rapid and complete surface drainage from the finished cover.

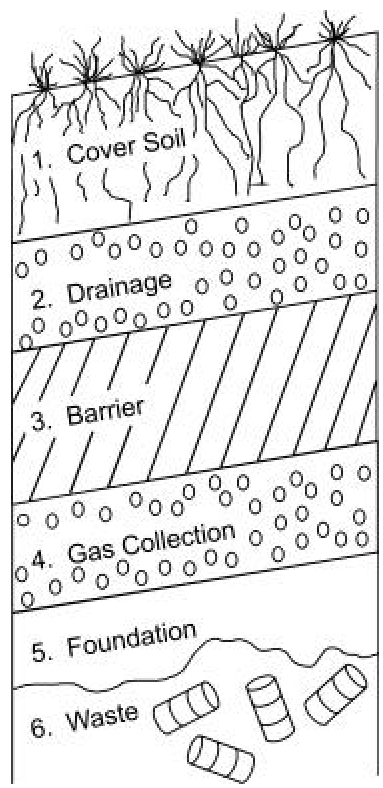

Figure 4. Typical Components of a Conventional RCRA Subtitle C Landfill Cover

There are many different configurations of conventional barrier-type landfill covers. In all configurations, however, the barrier layer is of paramount importance and must have a very low hydraulic conductivity. As discussed in Section 3.1, the type of waste, the climate, and other variables require different components in the cover. Table 2 summarizes the primary functions and typical materials used in various layers of a conventional barrier-type cover. These components are discussed in more detail in the following sections.

Table 2. Components of Conventional, Barrier-Type Landfill Covers

Layer	Primary Function	Typical Composition
Cover Soil	• Control water and wind erosion • Support vegetation • Store water • Protect from freeze-thaw cycles	• Topsoil • Gravel or cobbles
Drainage	• Quickly remove infiltrating water • Protect barrier layer from freeze-thaw damage • Maintain stability	• Sand and/or gravel • Geonets • Geocomposites
Barrier	• Stop downward flow of water • Control gas flow from the waste	• Compacted clay • Geomembranes • Geosynthetic clay layers • Geocomposites
Gas Collection	• Transmit gas to collection points for removal	• Sand and/or gravel • Geosynthetics
Foundation	• Separate cover from waste • Provide correct land surface slope	• Soil • Geotextile filters

At present, conventional barrier-type covers represent the predominant final landfill cover technology. Although there are many variations in specific design details, some or all of the functional layers described above can be found in nearly all existing landfill covers. Additional components may be added to the functional layers described above to meet the specific requirements at a site. For example, gravel may be added to the surface soil in desert regions to control wind erosion, or animal intrusion layers of cobble-size stone may be added, usually below the cover soil layer, to protect hazardous radioactive waste sites. A more complete discussion of conventional covers may be found in the technical literature [34][35][40][59].

3.2.1.1 The Cover Soil Layer

The primary function of the surface layer is to control wind and water erosion by supporting an adequate vegetative cover. The soil should have adequate physical properties to store sufficient water for plant use, as well as chemical properties to provide the necessary nutrients for plant growth. Fertilizers or other soil amendments may be required to establish a good surface layer. Selecting an appropriate vegetative species is essential for the proper functioning of the surface layer. A mixture of grasses is the preferred vegetation. Each of the grass species should be indigenous to the area, hardy, and drought-resistant. This is important both for aesthetic reasons and to ensure that surface erosion is controlled.

The cover soil layer is usually about 0.6 m (24 inches) thick. The thickness of soil cover needed depends on the climate, soil properties, and vegetation type. A protection layer is sometimes installed under the vegetation rooting zone—but as part of the cover soil layer—to keep the barrier layer from freezing. The surface slope should preferably be at least 2.5 percent, where feasible, to ensure adequate surface drainage after landfill settlement, and should be less that 5 percent to reduce erosion and maintenance problems. Steep slopes may require special techniques to stabilize the cover soil against landslides. Landslides are of particular concern where materials with slick surfaces (e.g., GM materials) are installed within the cover.

In arid regions, gravel or cobbles are sometimes used as the exposed surface of the cover soil layer to control erosion. These covers may not support vegetation, and as a result, significant volumes of precipitation may percolate below the cover into the drainage layer during heavy rains. Concrete covers are sometimes used for erosion control, but they may leak substantial volumes of water. Asphalt is also sometimes used as surface cover, but asphalt must be protected from sunlight and oxidation or it will deteriorate.

A layer of cobbles may be placed below the soil cover layer to form a barrier to plant roots and burrowing animals. These "bio-intrusion" layers have been installed at sites with radioactive wastes to protect the barrier layers below and to ensure the control of radioactive gases. Although animals generally cannot penetrate a flexible membrane cover (FMC) layer, they can widen an existing hole or tear through wrinkled material [30]. Studies have shown that animal burrows do not significantly affect percolation of water into landfill covers [24]. As a result, bio-intrusion layers are typically not included as a component in most landfill covers for non-radioactive wastes.

3.2.1.2 The Drainage Layer

Water that penetrates through the cover soil and is stopped by the barrier layer should be removed laterally by a drainage layer built of highly permeable material. Rapid drainage reduces the hydraulic head on the underlying barrier layer, thus reducing infiltration. Drainage also improves slope stability by reducing pore water pressure. In addition, rapid drainage provides aeration for the plant roots growing in the cover soil. The most common materials used for the drainage layer are sand, gravel, and manmade geosynthetic materials.

Geonets are manmade drainage layers that are thin and have a grid-like character that provides extensive flow opportunity. McBean et al. [40] give an example of a 4.5-mm ($^{3}/_{16}$-inch)-thick geonet having a transmissivity equivalent to 0.3 m (1 foot) of sand. The use of geonets can substantially reduce cover thickness, and they are easier to place than sand layers. The properties of geosynthetic materials suitable for use in drainage layers are discussed in greater detail by Koerner and Daniel [34].

All drainage materials must be separated from the overlying soil by adequate filters or filter fabrics to prevent the overlying soils from clogging the drainage material. Geotextiles are flexible, permeable materials usually manufactured from manmade fibers. They are frequently used as filters to prevent the movement of soil particles into drainage systems. Geotextile filters should be placed over the drainage layer.

3.2.1.3 The Barrier Layer

The hydraulic barrier layer is naturally the central element of conventional landfill covers using barrier technology. The barrier layer minimizes percolation of water from the overlying layers into the waste by opposing the natural flow of water downward in response to gravity. The barrier layer is often referred to as an "impermeable" layer although no material commonly used as a barrier is impermeable when new and most of them deteriorate with age. Therefore, the drainage layer lying above the barrier should quickly remove any water that accumulates above the barrier and is a required element of the cover.

CCLs—the most commonly used barrier layers—are typically about 0.6 m (24 inches) thick and have a saturated hydraulic conductivity (K) equal to or less than 1×10^{-7} cm/sec. CCLs are constructed in layers (called "lifts") using naturally clay-rich soils. CCLs used in final cover systems should remain ductile to accommodate differential settlement and must be protected from desiccation to reduce cracking, which increases the saturated hydraulic conductivity (K value) of the soil. CCLs should be protected from freezing because freezing and thawing can greatly increase the K value. Where suitable soils are not available, bentonite (a refined, sodium-saturated clay) may be added to native soils to achieve the required K value. Soil compaction is necessary to decrease the porosity of the soil. The minimum K value is normally associated with maximum compaction. The degree of compaction is dependent on the water content of the clay and is achieved in a relatively narrow range of soil-moisture content. The optimum water content of clay for compaction must be determined for each clay source. Koerner and Daniel [34] caution that "it is easier to build a low-hydraulic-conductivity CCL than it is to design a final cover system that will adequately protect the CCL from forces that tend to drive the conductivity above the design value."

Other materials can be used as barrier layers. Typically, a GM is used in a "composite" barrier design in combination either with a CCL or with a geosynthetic clay layer to achieve the required design performance. GMs used as barrier layers in landfill covers are called flexible membrane covers (FMCs). FMCs are usually not exposed to leachate, so chemical compatibility is not an issue. However, FMCs are subject to substantial strains due to settlement of the waste and must resist penetration by construction equipment, rocks, and roots. Therefore, their strength and elasticity are important properties. They are often required to be at least 40 mils thick to provide adequate strength and other properties.

The most common materials for FMCs in final covers are as follows:

- High-density polyethylene (*HDPE*)
- Linear low-density polyethylene (*LLDPE*)
- Polypropylene (*PP*)
- Polyvinyl chloride (*PVC*)

Some of the properties of these materials are summarized in Table 3.

FMCs typically have few pinholes, and vapor diffusion is very slow; as a result, little water moves through the material. Installation mishaps, however, may result in punctures, tears, or incomplete seams, which are likely to allow the passage of some water through the barrier layer. Therefore, construction quality control is a critical factor in FMC performance. FMCs arrive on site in 6-15 m (20-50 ft) wide rolls, making field seaming a very large endeavor. The seams should obviously not leak, but in addition, they should also be physically strong and maintain their integrity over a long period of time. Temperature is an

Table 3. Some Properties of Synthetic Materials Used in Landfill Covers

Material	Leachate Compatibility	Biaxial Strain	Seam Integrity
HDPE	Very good	Poor	Good
LLDPE	Good	Very good	Very good
PP	Very good	Very good	Very good
PVC	Good	Very good	Very good

Adapted from ASCE, 1997 [5]

important consideration during FMC installation and may seriously impact the installation schedule. Installation is usually restricted to periods when the ambient temperature is in the range of 5°C–40°C (approximately 40º-105°F). Quality-control testing is typically performed on geomembrane liners after installation and similar testing should be performed on FMC cover layers to verify the integrity of the installed FMC.

Geosynthetic clay layers (GCLs) are manufactured rolls of bentonite clay held between geotextiles or bonded to a GM. Most sodium bentonite GCLs have K values near $1x10^{-9}$ cm/sec. GCLs are generally equivalent or superior to CCLs in final covers, with the exception of field installation issues [34].

3.2.1.4 The Gas Collection Layer

The decomposition of wastes and evaporation of organic compounds within a landfill produces gases, some of which are toxic or flammable. Aerobic biological processes occur when oxygen is available to the waste, generally immediately after its disposal. The primary gaseous product of this activity is carbon dioxide. After oxygen is depleted from the waste zone, anaerobic bacteria become dominant and both carbon dioxide and methane gas are produced. Lesser components of landfill gas include hydrogen sulfide, nitrogen, and hydrogen. In addition, any volatile organic compounds (VOCs) in the deposited waste or produced by later chemical reactions may be present in landfill gas.

The presence of explosive or toxic gases underground presents a potential problem to nearby buildings and/or to personnel working in the vicinity of the landfill. Gases follow preferential flow paths both upward and laterally and either ultimately vent to the atmosphere or accumulate under a natural or manmade resistant layer. To prevent accumulation, gases are often collected via active or passive systems and disposed of in a controlled manner. Any cover that employs a barrier layer is likely to require a gas control system because the barrier will likely trap gas below the cover. Even low gas-production rates may yield dangerous volumes of explosive and/or poisonous gas if trapped below a barrier within the cover.

The rate at which municipal waste generates gas increases for the first 5 or 6 years after placement in a landfill, may remain relatively constant while the landfill is active, and declines thereafter. The rate of gas production depends on many factors, but because military landfills are generally old when covered, they are likely to produce only small amounts of landfill gas after cover placement. The placement of a cover will inherently reduce the rate of gas production because the intent of the cover is to stop water from moving into the waste. Continuing biological gas production will carry off a portion of the moisture and will gradually dry the waste. Therefore, the use of non-barrier alternative covers without gas controls may be a viable alternative for military landfills and has the potential advantage of reducing remediation costs. Gas control in landfill covers is discussed in greater detail in Section 7.1.8.

3.2.2 RCRA Subtitle D Covers

RCRA Subtitle D covers are modified, barrier-type covers (Figure 5). From the surface downward, these covers include a ***grass cover***, ***topsoil*** layer, and a layer of ***undefined soil*** that is compacted to yield a K value of $1x10^{-5}$ cm/sec [6][80]. The subtitle D cover meets the federal criteria for Municipal Solid Waste Landfills, 40 CFR, Part 258.60, Closure Criteria. This cover, which may also be called a compacted soil cover, is less expensive than conventional barrier-type covers and has been approved by regulators for use in dry climates. It is a barrier cover because it relies on compaction to create a layer of soil with reduced hydraulic conductivity. However, the topsoil layer is generally no more than 0.15 m (6 inches) thick, potentially leaving the barrier layer exposed to freezing and root intrusion. Either of these approaches is likely to increase the K value of the soil over time. There is no requirement for water-holding capacity within the soil cover. Therefore, after the soil is loosened by freezing and root activity, the cover may not control movement of precipitation into the waste if the plant-available soil water-holding capacity is low. Thus, it may not ensure long-term protection against infiltration of precipitation into the waste.

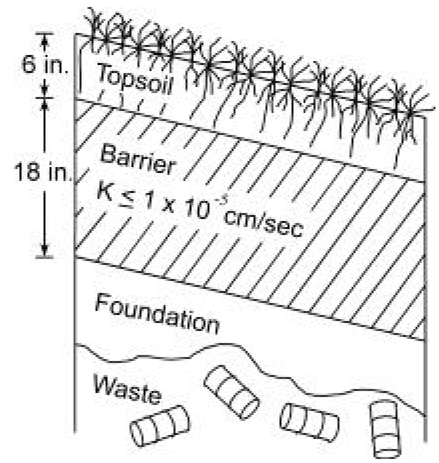

Figure 5. The Subtitle D Cover

3.3 Innovative Landfill Covers

Innovative landfill covers discussed here have all undergone at least experimental verification in field tests although some have not been used on large areas. For those covers with more complete descriptions in the literature, the discussion here will be brief.

3.3.1 Innovative Non-Barrier Landfill Covers

In arid and semi-arid regions where evaporation exceeds precipitation, landfill covers should be capable of storing infiltrating water in the cover soil until it is withdrawn by plants. This will prevent precipitation from reaching the waste. These covers are called soil-plant covers, natural covers, earthen barriers, monofill covers, or monocovers. One specific variation is called the evapotranspiration cover, or ET cover.

3.3.1.1 The Evapotranspiration Cover

The ET cover concept is an innovative cover design that differs from the other innovative covers in two important ways:

- It uses natural systems with no barrier layers
- The concept has been widely demonstrated in natural systems over long periods of time.

The ET cover is designed to provide adequate soil water-holding capacity and soil that will support rapid, robust root growth. The design principles for the ET cover are well known, and the potential cost savings to the Air Force are substantial. However, the relative newness of the concept requires that an ET cover design be carefully evaluated for a specific site to determine that it can meet the performance requirements. The design must be well documented to satisfy the regulators that the performance requirements will indeed be met.

The ET cover consists of a layer of soil covered by native plant species. Depending on site conditions, the ET cover may be composed of different soil layers. However, each soil layer must support robust root growth. As shown in Figure 6, the ET cover contains no barrier or impermeable layers. The soil provides a reservoir to hold water infiltrating from precipitation on the surface. Adequate soil depth must be provided to hold the water from the most critical series of storm events. Natural evaporation from the soil plus plant transpiration (ET) then empties the soil water reservoir [27][29]. The ET cover is a practical, easily maintained, biological system that will remain effective over extended periods of time, perhaps centuries, at low cost.

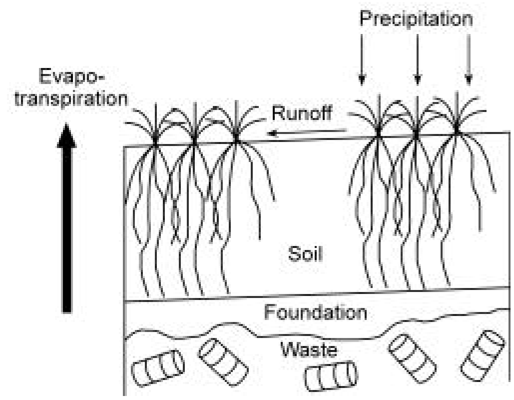

Figure 6. The ET Cover

Climate is a primary determinant of whether or not an ET cover is practical for a given site. The ratio of evaporation-to-precipitation is naturally most favorable in arid and semi-arid areas. It is estimated that properly designed ET covers could prevent infiltration into landfill wastes in most of the United States west of the Mississippi River as shown in Figure 7 [28]. Depending on site-specific conditions, an ET cover could minimize infiltration at landfills in much of the rest of the country and warrants evaluation at these sites to see whether it will provide a cost-effective design.

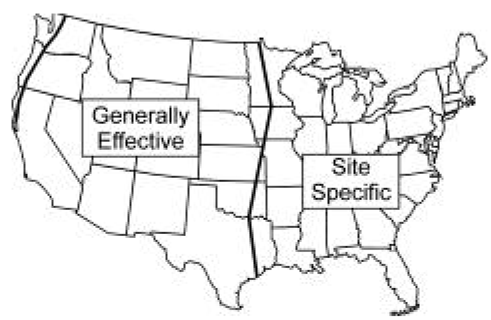

Figure 7. Regions Where ET Covers Are Effective

Successful application of the ET cover requires good engineering design. The ET cover differs from other proposed soil vegetative covers because the design is based upon the following minimum criteria:

- The soil physical properties must allow the most rapid and complete root growth possible for the plants growing on the cover. Good physical properties require a soil bulk density between 1.1 and 1.5 g/cm^3 (68–94 lb/ft^3). [Bulk soil density should be adjusted downward if indicated by site conditions.]
- The soil water-holding capacity that is plant-available must be great enough to hold all soil water accumulated during critical design periods.
- The soil store of plant-available nutrients should be adequate to support robust plant growth both immediately and for an extended period into the future via nutrient cycling within the ecosystem.
- The vegetation growing on the cover should be a mixture of grasses that are native to the site. Grass cover is specified because grass provides the optimum erosion control.

However, for sites at which grasses are not the dominant native plants, the design should be modified to select other appropriate native plant species.

The ET principles were well understood years ago. Only in the last decade, however, has this knowledge been brought to bear on the problem of covering landfills and other wastes. Cole and Mathews' classic paper reported the results of water balance experiments from five locations in the Great Plains extending over the years 1907 to 1936 [15]. Each location included data from wheat grown every year (continuous wheat). Two locations had continuous measurements from beneath native sod, and the other locations had partial records for native sod. Their analysis of 30 years of data clearly demonstrated that water did not move below the root zone of native grass or continuous wheat at any of these five locations. Even though the continuous wheat lay fallow for 3 to 7 months each year, no water moved below the root zone.

Further proof of the long-term reliability of the ET cover concept is provided by Aronovici [7]. Soil water content, chloride concentrations, and salt movement in the soil profiles were measured under continuous native grass near Amarillo, Texas. Both dry land and irrigated land were examined from the surface to a depth of 15 m (50 feet). Mean annual precipitation is about 470 mm at that Southern Plains location. The surface soil is Pullman clay loam, which cracks extensively when dry and was historically populated by prairie dogs and small burrowing animals. The soil extending to the 15 m depth was described as containing many root and worm hole casts throughout the whole profile ranging in size from less than 1 to 5 mm. The soil offered numerous preferential flow paths from the surface to the 15 m depth. He found that the soil water content was at or below the plant-wilting point from 1 m below the surface downward. Chloride and electrical conductivity data showed large accumulations of the chloride ion and salts from 0.9 to 1.8 m (3-6 feet) under native grass. However, the chloride and salt front were both displaced downward by percolating water to about 2.4 m (8 feet) under both dry land cropping and minimum irrigation regimes, and to well below the 9 m (30-foot) depth under heavy irrigation. Aronovici concluded "*There has been little or no deep percolation on native or revegetated grassland within historic time where natural surface drainage occurs.*"

The ET cover is less costly to build than conventional covers because it requires no barrier layers and no drainage layers. For illustrative purposes, construction costs for a conventional single-barrier RCRA cover, a two-barrier RCRA cover, and a comparable ET cover were estimated for a site in the southern Great Plains. Published cost figures [50] were used for all items except grass establishment, which was obtained from local vendors. It was assumed that the conventional covers would consist of a typical 0.6 m (2-foot) thick layer of cover soil, a drainage layer, a 0.6 m (2-foot) thick compacted clay barrier, or a two-barrier system using a GM over the clay barrier. Both conventional covers were assumed to require a gas collection system, which is typical with barrier cover designs. The ET cover was assumed to consist of a 2 m (6.5-foot) thick soil layer, and the cost was estimated both with and without a gas collection system. At landfills that produce little gas, such as the older landfills at Air Force installations, a gas collection layer would typically not be needed under an ET cover. Each cover was assumed to require a 0.6 m (2-foot) thick foundation layer to establish correct surface grade under the cover, and each was covered with native grass on top. Equipment mobilization to the site and other indirect costs common to any landfill cover construction were not included in the calculations. The estimated construction costs are summarized in Table 4. Construction costs for the ET cover ranged from 35 percent to 72 percent of the costs of conventional RCRA covers. Typically, the ET cover should cost less than half as much to build as a conventional cover.

Table 4. Comparison of Landfill Cover Construction Costs

Cost Item	ET Cover	Conventional Single Barrier	Conventional Double Barrier
	(dollars / hectare)	(dollars / hectare)	(dollars / hectare)
Soil cover placement	$130,100	$43,400	$43,400
Water drainage layer	--	98,400	98,400
Geomembrane barrier layer	--	--	118,400
Compacted clay barrier layer	--	92,700	92,700
Gas collection layer	98,400	98,400	98,400
Common fill, foundation	43,400	43,400	43,400
Grass establishment	2,600	2,600	2,600
Total (with Gas Collection)	**$274,500**	**$378,900**	**$497,300**
Total (without Gas Collection)	**$176,100**	**NA**	**NA**

From Mitretek Systems [27]
1 Hectare = 2.47 Acres

The ET cover is a self-renewing natural system. Thus, maintenance costs are minimized. If a depression, crack, or hole develops on an ET cover, it can be repaired simply by filling with soil to reestablish grade and replanting the grass cover. Repair of a conventional cover requires excavating the damaged area and rebuilding the cover layer by layer, which is much more expensive.

Mitretek Systems [43] used Air Force data to estimate the potential cost savings resulting from using the ET cover design rather than a conventional barrier-type cover at sites where the climate favors the ET concept. They estimated that application of the ET cover on currently unremediated Air Force landfills could result in potential savings of more than $500 million in landfill cover construction.

3.3.1.2 Other Soil-Plant Landfill Covers

Despite obvious similarities, soil-plant landfill covers are discussed separately from the ET cover because they have often been designed with insufficient water-holding capacity to withstand a series of severe storms. Furthermore, during construction of the soil-plant covers, the soil was sometimes so compacted that it limited or prevented adequate root growth. For example, Warren et al. [79] reported the results of a four-year experiment with four landfill covers at Hill Air Force Base (AFB) in northern Utah. Their experiment included a control plot with soil and vegetation only, a RCRA barrier-type cover, and two capillary-barrier covers. The capillary-barrier covers were similar to the soil-vegetation cover with two exceptions: the soil was thicker, and they had a capillary barrier under the fine soil layer. Each of the four treatments was seeded with grass; however, one capillary barrier included both grass and shrubs in the cover. The quantity of leachate (the water moving into the waste) was measured for 46 months. The results are summarized in Table 5.

Because the site has a dry climate, one would expect both the soil-vegetative and capillary-barrier covers (described in Section 3.3.2.1) to work as well as the RCRA barrier-type cover. The soil-vegetative cover produced more leachate than the capillary barriers, probably because the soil layer was thinner, thus it could hold much less water. The authors note that most leachate was produced during early spring and resulted from snowmelt, early rains, and low evaporation potential.

Table 5. Leachate Production during 46 Months under Four Landfill Covers

Soil Depth (cm)	Treatment	Leachate (cm)
90	Soil-vegetative, (control)	41
120	RCRA, barrier-type	0.01
150	Capillary barrier	24
150	Capillary barrier (+ shrubs)	30

From Warren et al., 1996 [79]

The most likely cause for the failure of the soil-vegetative cover at Hill AFB, and probably other sites as well, was excessive compaction of the soil. Several factors may limit growth of plant roots; soil bulk density is one soil property known to exert major control of root growth. Plant roots grow well in most soils having bulk densities of 1.1 to 1.5 g/cm^3 (69-94 lb/ft^3), moderately well in soils having bulk density up to 1.7 g/cm^3 (106 lb/ft^3), and poorly or not at all at higher soil bulk densities. Water can move rapidly to roots through only a few millimeters of soil. Soil water more than a few millimeters away from roots moves slowly, if at all, toward the root mass. Therefore, to ensure rapid, effective soil-water removal from soil, roots must fully explore layers from which water is to be withdrawn by plants.

Warren et al. [79] reported that they compacted the soil in all treatments, including the soil-vegetative cover, to a bulk density of 1.86 g/cm^3 (116 lb/ft^3). The soil density was even greater than that of the compacted clay in their RCRA cover (1.76 g/ cm^3 or 110 lb/ft^3). Soils with high bulk density have a reduced water-holding capacity. High soil density may have reduced or prevented adequate root growth below the top few centimeters of the soil profile and reduced water-holding capacity in these experiments. Thus, high soil density may account for the failure of the three soil-vegetation covers in the study [79].

3.3.2 Innovative Barrier-Type Landfill Covers

The innovative barrier type covers, discussed in the following sections, are new approaches for designing barrier layers and not complete cover systems. Some of them have not been used on large areas. The discussion is brief for those with the most complete descriptions in the literature.

3.3.2.1 Capillary Barriers

Capillary barrier covers consist of a series of layers that include (from the surface downward) a layer of fine soil over a layer of coarser material (e.g., sand or gravel) (Figure 8). The purpose of the capillary barrier is to increase the water-storage capacity of the fine soil layer. The barrier is created in this type of cover by the large change in pore sizes between the layers of fine and coarse material [6][24][56]. Capillary forces cause the layer of fine soil overlying the coarser material to hold water between the field capacity and saturation. Normally, the fine-grained layer would drain to the field capacity over a period of one to three days. Thus, the fine soil will hold more water than if there were no change in particle size between the layers. This type of barrier, however, can fail if too much water accumulates in the fine-particle layer. This allows the release of water into the coarser layer beneath it, which will be breached under these conditions because the coarse layer provides no barrier to water flow. Lateral drainage, evaporation, and/or plant transpiration remove water stored in the soil above this type of barrier. It has been used primarily in experimental installations.

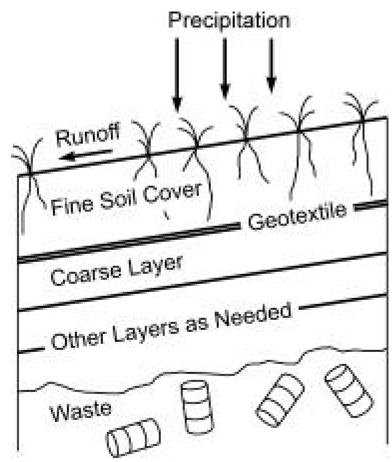

Figure 8. The Capillary Barrier Cover

A capillary barrier is effective if the combined effect of ET and lateral diversion exceeds the infiltration from precipitation, thereby keeping the system sufficiently dry so that breakthrough does not occur. These systems have been suggested for application in dry climates.

Whereas capillary forces in the soil prevent breakthrough of the water into the gravel at soil moisture conditions less than saturation, when saturation occurs, breakthrough of water will take place and the capillary barrier fails. By placing the interface between the soil and gravel on an incline, lateral flow at pressures less than atmospheric can occur. Stormont [55] found that alternating fine and coarse layers was effective over lateral distances of 7 m (23 ft) on a 10-percent slope. He also found that a single capillary-barrier layer failed under the conditions of his tests.

The advantages capillary-barrier systems have over clay hydraulic barriers are that they are not subject to desiccation and cracking and they may be less expensive to install. The addition of the coarse layer increases soil water-holding capacity but also increases construction costs. The capillary barrier is particularly advantageous in locations where soils with high water-holding capacity are unavailable or too expensive. Experimental field experience with soil-gravel capillary barrier systems shows that they will fail periodically although they perform better than the fine soil cover without the coarse layer below [47][79].

3.3.2.2 Dry Barriers

Dry barriers are a modified version of a capillary barrier. They are particularly desirable in situations where the capillary barrier may fail. However, the literature did not address the water-holding capacity of the coarse layer (it will be small) or the airflow rate required to remove the water as it infiltrates the coarse layer. Dry barriers appear to hold promise, but the literature search did not reveal sufficient engineering design data to encourage its use except on an experimental basis.

As illustrated in Figure 9, the dry barrier cover system, sometimes called the convective air-dried barrier, is similar to the capillary-barrier cover except that wind-convective or power-driven airflow through the layer of coarse material helps remove water that may infiltrate this layer [6]. Dry barriers may be suitable for landfills in hot, arid climates. They have been used as a component of other covers in experimental systems.

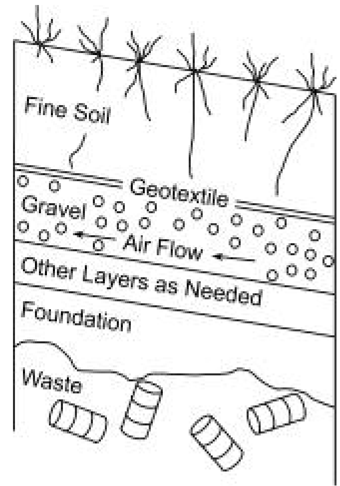

Figure 9. The Dry Barrier Cover

3.3.2.3 Asphalt Barriers

Asphalt barriers may replace compacted clay in arid climate landfills where a clay barrier may fail because of desiccation [24]. Both oxygen from the air and ultraviolet radiation from sunlight can deteriorate asphalt. Therefore, the asphalt-barrier layer must be buried below a surface-cover layer to protect the asphalt. The asphalt barrier should also be buried below the frost line so that soil movement due to frost heaving will not damage the asphalt. This barrier layer is still experimental and is proposed as a rather costly alternative barrier for use in landfill covers over radioactive wastes. Asphalt barriers do not appear suitable for widespread use on Air Force landfills, though they may be suitable for experimental use.

Modified asphalt paving has been proposed as an alternative surface layer material in applications where it is desired to allow heavy equipment continued access to the site. Polymers are added to the asphalt binder to reduce the air voids in the binder and thus reduce infiltration through the asphalt mix. This approach appears promising as a possible remediation for some sites, but there is presently insufficient information to determine whether it will be suitable and approved as the barrier layer for a landfill cover. An EPA SITE Program demonstration of this material is scheduled during 1999.

3.4 Other Landfill Remediation Components

Other components may be required in addition to a surface cover to contain landfill wastes. Landfill gas, leachate, and contaminated groundwater must all be controlled to achieve complete containment. Landfill gas and leachate are discussed in the following sections.

3.4.1 Landfill Gas Collection and Disposal

A properly designed landfill cover will decrease odors and minimize vertical migration of landfill gas. However, the resistance to vertical gas movement imposed by some cover designs increases the potential for trapping gas under the cover or for lateral migration of potentially explosive or toxic gas to nearby buildings or other receptors. To prevent this, passive or active gas collection and transport may be installed within the cover to collect gas for disposal.

Lateral movement of landfill gas can be intercepted either by permeable or impermeable control systems. Permeable gas interception systems capture the gas and conduct it to the surface for recovery or disposal. The gas collection layer described in Section 3.2.1.4 is one example of permeable collection system. Other alternatives include perforated pipes and/or horizontal trenches, filled with sand or other permeable material, to provide a pathway for gas flow. These should be installed at intervals over the top of the waste before final cover installation. In situations where the final cover is already in place, vertical wells drilled into the top of the waste may be used to collect gas. Non-barrier landfill covers, such as the ET cover, allow the landfill gas to move through the cover soil across the entire surface of the landfill. These covers may require no additional gas collection or disposal facilities.

Impermeable gas interception systems block the lateral flow of the gas and also provide conduits to the surface. Typical components of impermeable systems are barriers made of clay or synthetic liners installed around the perimeter of the landfill to prevent off-site migration. These are frequently used in conjunction with a permeable gas collection trench installed around the perimeter just inside of the barrier.

Landfill gas collection systems are divided into two main groups: passive systems and active systems. Active systems use mechanical means to move the gas to the surface. Major system components generally include gas extraction wells, gas collection headers, vacuum blowers or compressors, and a gas treatment or recovery system. Active systems are typically used at landfills with severe odor problems, and/or active landfills containing readily biodegradable waste and producing substantial quantities of gas. An active gas collection system should be considered if homes or buildings are (or plan to be) located near the landfill because of the significant risk if gas migrates. The gas may be disposed aboveground or may be processed for methane recovery if there is sufficient volume to make recovery economically viable. It is unlikely that any Air Force landfill will generate enough gas to make methane recovery practical.

Passive landfill gas control systems provide a pathway for the gas but do not use mechanical components. Instead, the natural pressure as the gas is formed in the landfill pushes the gas into the collection system. Passive gas control systems will probably be sufficient for most Air Force landfills.

Safe disposal of the collected gas is usually accomplished by venting to the atmosphere and/or by burning the gas in a flare. Venting is inexpensive and may provide a satisfactory solution if the volume of gas is not large and no homes or buildings are nearby. Vents require little or no maintenance, but must be protected in such a way that snow or ice will not block the vent opening. Flares may be required in situations where homes or buildings are close to the landfill, when final use of the site includes allowing public access, when the landfill produces excessive odors, or when state or federal air standards are violated by the release of the landfill gas. Installation of a flare requires a commitment to long-term maintenance to ensure its continued operation.

3.4.2 Leachate Collection and Treatment

The design and installation of leachate collection and treatment systems is typically done as part of the original construction of a modern landfill. Under current regulations, a new landfill must have a liner system to minimize the release of leachate into the groundwater. RCRA Subtitle C regulations specify that a leachate collection system must be installed and operated so as to maintain the leachate at a depth of no more than 0.3 m (1 foot) above the liner. However, most Air Force landfills are older facilities that were constructed before the current regulations went into effect, were constructed without liners or leachate collection systems, and have been inactive for many years. A recent survey of Air Force landfills found that less than 1 percent have a liner system [43]. Some of these sites have no problem with leachate contamination, and no leachate collection or treatment is required.

At some landfill sites, leachate may be found emanating as seeps from the landfill's side slopes or from nearby embankments or as contaminants in groundwater or surface water. If the landfill has no bottom liner and/or leachate collection system, a subsurface drain or a series of extraction wells may be installed around the perimeter of the waste fill as a leachate collection system. The depth of the waste, as well as the hazards associated with excavating landfill material, usually prevents installation of drains within the landfill. Maintenance of the drain or wells is crucial because the permeable layer is prone to fouling due to biological growth or precipitation of metal hydroxides.

Landfill leachate typically has high biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), as well as high concentrations of metals. Table 6 shows the typical constituents in landfill leachate and their expected concentration ranges [64]. The large concentration ranges shown in Table 6 are due to the variations between leachates from different types of landfills, the variations in the waste of landfills of a similar type, and the possibility that individual samples may be diluted by groundwater.

The treatment of leachate employs the same technologies as the treatment of high-strength industrial wastewater and may include biological treatment to reduce the BOD_5 and COD and chemical treatment for the removal of metals. Treatment may be done on site, or the leachate may be discharged to a sewer system for off-site treatment. Direct discharge to a publicly owned treatment works (POTW) may be appropriate if the leachate stream is amenable to the treatment provided by the POTW. The POTW may have limitations stipulated in their National Pollutant Discharge Elimination System (NPDES) discharge permit (e.g., heavy-metal limitation) that will preclude accepting the leachate for treatment. In these cases, pretreatment is required before discharge to the POTW.

3.4.3 Groundwater Treatment

Groundwater contamination may result from the migration of leachate from a landfill or if the waste lies below the water table and the groundwater flows through the landfill waste. The design and implementation of containment to control and prevent the migration-contaminated groundwater may be included with the closure of the landfill or may be handled as a separate remediation project. Groundwater control measures frequently employed include the following:

- Collection drains or trenches
- Slurry walls
- In situ treatment walls (e.g., zero-valent iron)
- Pump and treat systems

Though not a truly a containment, natural attenuation may also be used to control the migration of contaminated groundwater once the source of water into the waste has been controlled. For more on groundwater control and treatment, see Section 5.8.3 on selecting remediation components, Table 15 in Chapter 6 for an evaluation of technology alternatives, and Section 7.5 on design of groundwater control.

Table 6. Landfill Leachate Characteristics and Common Constituents

Constituent	Concentration Range (mg/L)	Typical Concentration Range (mg/L)
Biochemical Oxygen Demand, 5-day (BOD_5)	4 – 57,700	1,000 – 30,000
Chemical Oxygen Demand (COD)	31 – 89,520	1,000 – 50,000
Total Organic Carbon (TOC)	0 – 28,500	700 – 10,000
Total volatile Acids (as acetic acid)	70 – 27,700	**
Total Kjeldahl Nitrogen (as N)	7 – 1,970	10 – 500
Nitrate (as N)	0 – 51	0.1 – 10
Ammonia (as N)	0 – 1,966	**
Total Phosphates	0.2 – 130	0.5 – 50
Orthophosphates	0.2 – 130	**
Total Alkalinity (as $CaCO_3$)	0 – 20,850	500 – 10,000
Total Hardness (as $CaCO_3$)	0 – 22,800	500 – 10,000
Total Solids	0 – 59,200	3,000 – 50,000
Total Dissolved Solids (TDS)	584 – 44,900	1,000 – 20,000
Specific Conductance (µmhos/cm)	1,400 – 17,100	2,000 – 8,000
pH (units)	3.7 – 8.8	5.0 – 7.5
Calcium	60 – 7,200	100 – 3,000
Magnesium	17 – 15,600	30 – 500
Sodium	0 – 7,700	200 – 1,500
Chloride	4.7 – 4,816	100 – 2,000
Sulfate	10 – 3,240	10 – 1,000
Chromium	0.02 – 18	0.05 – 1
Cadmium	0 – 17	0 – 0.1
Copper	0.005 – 9.9	0.02 – 1
Lead	0.001 – 2	0.1 – 1
Nickel	0.02 – 79	0.1 – 1
Iron	4 – 2,820	10 – 1,000
Zinc	0.06 – 370	0.5 – 30
Methane Gas (percent composition)	(Up to 60%)	**
Carbon Dioxide Gas (percent composition)	(Up to 40%)	**

NOTE: Based on data collected by the U.S. Army Corps of Engineers, construction Engineering Research Laboratory [64].

** No data provided.

4 Site Characterization

This section describes the processes for gathering information needed to support the decisions to select and design the site remediation. Characterization is not limited to the landfill site alone; it also includes the surrounding area. The site characterization activities fall into three phases: collecting existing site information, reviewing data for missing information, and performing field investigations to fill data gaps. Some of the information may be collected by the RPM and/or base personnel, and other information will be collected and reported by contractor personnel.

The following sections discuss the more important information needed to characterize the site, where the information may be found, and the procedures and protocols for field investigation to obtain missing information.

4.1 Objectives of Site Characterization

The site characterization will provide the factual information upon which all decisions in the closure process will be based. The required information falls broadly into the following categories:

- Operating history of the site
- Existing site conditions
- Geology, hydrology, and topography of the area
- Nature and extent of environmental contamination
- Surrounding land use and proposed future use of the site

The information, once collected, will be used to support the decisions leading to the development and selection of remediation alternatives and to provide the necessary data for engineering design of the selected remediation. The final selection of a closure alternative will typically be based upon a streamlined assessment of risks to human health and the environment. The information collected during the site characterization must be sufficient to make the decisions outlined in the *Decision Tool for Landfill Remediation* [44], which is described in Section 5.1.1.

4.2 The Existing Facility

The initial phase of site characterization is to document what is known about the operating history of the landfill, how it was constructed, and the current conditions at the site. This phase might begin with a site visit and a search through base records. The site visit should include detailed observations of the site conditions and contacts with base personnel. Present site conditions should be considered in terms of the following:

- Present conditions that will require remediation
- Future plans for the site or for neighboring sites that will impact or limit the selection of a remediation
- Restrictions in site access or other physical limitations to constructing the selection remediation

Table 7 lists some specific questions to consider during the site visit. The search of base records may include accessing a number of sources, including Environmental Management (EM) and the base Civil Engineer. Table 8 lists documents that typically are good sources of useful site data. Base personnel may be able to provide additional sources of information about the site and its history.

Table 7. Suggested Site Visit Questions

- What is the thickness of the existing intermediate or temporary cover?
- What are the existing cover slopes?
- Is the drainage adequate, or is there evidence of ponding?
- Is there evidence of surface erosion by wind or water?
- Is there evidence of groundwater or leachate seeping from the ground either on the site or into nearby ditches or streams?
- Is the site covered by vegetation and if so, what kind (e.g., grasses, bushes, trees)?
- What is the condition of the vegetation? (lush growth, dead spots, etc.)
- Are there any trees within the area to be remediated?
- Is the waste covered or are exposed waste piles observed at the site?
- Is there any large debris or construction/demolition waste on the surface?
- Is the access road suitable for bringing construction equipment onto the site?
- Are there overhead obstructions that would limit access by well-drilling or construction equipment?

Table 8. Sources of Historical Site Data

- Base Management Action Plan (MAP)
- Previous remedial investigation/feasibility study (RI/FS) and site inspection studies of the landfill site or nearby sites
- Base waste disposal records
- Permits and correspondence with regulators regarding the landfill or neighboring sites
- Air photos of the base taken at various times in the past (Note: historical air photos may also be available from commercial sources)
- Construction drawings of the landfill (if any)

4.2.1 Site Location

Information about the site location will be used in the remediation planning and in regulatory negotiations. The required information will include the following:

Site location. A physical description of the site location and a description of the site boundaries will be used in contracting and permitting documents. It is important to determine if the existing documents accurately "define" the landfill site, or if the description includes a much larger area than is supported by evidence of disposal activities. The proximity of the site to the base boundary should also be noted.

Site access. The location of access routes to the site will be used in remediation planning. Specific information regarding the locations of fences, trees, utility lines, and other overhead obstructions will be useful.

Geographical features in the area. A description of any geographical features, such as hills and streams, will be helpful during the remediation planning stage. Current topographic maps showing the land surface contours are very useful, if available.

Existing facilities in the area. A description of any above- or below-ground facilities, including utility trenches, in the area around the site will be helpful during the remediation planning stage.

Site land use. Current land use and proposed future use at the landfill site should be documented. The proposed future land use may impact the selection and construction of the site remediation. For example, the proposed use of a landfill site as a golf course may significantly increase the cost of covering the landfill to prevent infiltration of the large quantity of water typically used to irrigate golf courses.

Neighboring land use. The current and proposed future use of the areas adjoining the landfill site may result in the completion of exposure pathways that must be considered during the site risk assessment. The proximity of residential areas, schools, and other structures may increase the potential for human exposure. Nearby groundwater wells used as a source of potable water are also a potential source for human exposure. The proximity of wetlands or other sensitive environments may increase the potential of environmental exposure and risk.

4.2.2 History of Operation

It is important to document the operating history of the landfill site. The periods during which it operated and the types of waste disposed will determine which environmental regulations apply. This information may be difficult to obtain for older landfills that have long been unused.

Base records should be searched to determine when each waste cell, trench, or pit was constructed, when it was in use, and when it ceased to receive wastes. If base records are incomplete or missing, it may be possible to estimate these dates from air photos showing activity at different times in the past.

The types of wastes disposed of in a landfill leads to its classification as (1) municipal or sanitary (basically household-type wastes), (2) hazardous, (3) radioactive, or (4) mixed waste. The waste classification directly impacts the cover design because of both the technical and the regulatory requirements. For example, radioactive waste requires longer-term storage and must consider the potential generation of radon gas. Air Force landfills typically hold primarily municipal type wastes, but many have received waste solvents, fuels, or other hazardous materials.

The physical form of the waste and its chemical properties are an important consideration in selecting the site remediation. Past practice at some facilities was to dispose of waste solvents by pouring the liquids into unlined trenches and mixing them with the native soil. This procedure is no longer allowed, but the soil and groundwater contamination remains where liquid disposal was practiced in the past. At other sites, waste solvents were drummed, and the filled drums were placed in the landfill. The presence of solvent disposal pits as part of the landfill will significantly affect the complexity and cost of the remediation effort required to close the site. Drums of solvents in the landfill constitute a "hotspot" that should be carefully documented for possible removal or other special attention. Similarly, the disposal of any military-specific wastes—such as munitions and other explosives—in the landfill must be documented because their presence will reduce the number of remediation options available and will usually increase the closure costs.

At some Air Force landfills, wastes were burned in trenches or pits. Where wastes were burned, even incompletely, it is likely that most volatile materials went into the air.

4.2.3 Existing Facility Construction

The physical layout and method(s) of construction used to build the existing landfill facility should be documented in as much detail as possible. This information will initially be used for planning, and a review of the available information will point out the gaps in present knowledge. Later, this information will be used as a basis for designing the selected remediation. The documentation of the landfill's existing construction should include the following (where applicable): a description of the waste cells, cover, erosion control practices, gas control, leachate control, and groundwater monitoring.

4.2.3.1 Waste Cells

Waste may have been deposited in several ways during the active life of the landfill. A common method is to place the waste against the side of an excavated area and compact the waste into place. A soil cover is placed over the waste at the end of each day to control disease vectors such as rodents, insects, and birds and to control odors and prevent wind-borne litter movement. The daily soil cover forms cells of waste material in the landfill. Similarly, the waste might be placed in trenches and covered with the soil excavated from the trench. The important information to collect regarding the waste cells is as follows:

- How was the waste placed in the landfill? Was it placed in cells with daily cover, or was it placed in pits or trenches and covered with the excavated soil?
- How big are the individual waste cells and what area do they cover?
- How deep do the waste cells extend below the existing ground surface (bgs)? Do the waste cells extend below the water table?
- Is the landfill lined with clay or a synthetic membrane liner to minimize or prevent the release of leachate into the groundwater?

As mentioned in Section 2.1.2, the RPM is cautioned against conducting exploratory investigations in the fill unless there is substantial prior evidence to indicate that significant "hotspots" of hazardous waste exist (see Section 5.4).

4.2.3.2 Cover

Landfill covers are used at various times during a site's active life. As mentioned above, a thin cover is placed over the waste at the end of each day to control odors, litter, and rodents. Intermediate covers are often used to protect areas of an active landfill that will not be covered with additional waste or a final cover for an extended time. Intermediate covers provide the same function as a daily cover and also encourage surface runoff. Typically, a landfill to be closed will not have a final cover in place, but it is possible that a landfill with multiple pits or cells may have one or more cells capped with a final cover.

Nearly all landfill covers already in place today are conventional, barrier-type landfill covers. Compacted clay and synthetic materials are common components in these barrier-type covers. The important information to collect about the existing covers is the thickness of each layer and the materials of construction. Copies of construction drawings and construction specifications should be obtained if available.

4.2.3.3 Erosion Control

Erosion of surface soil from a cover can be a serious problem. Not only can the efficacy of the cover be diminished, but downstream environments can also be adversely affected. Observed erosion problems should be documented. In addition, maps of the area topography should be collected, along with descriptions of the existing surface water management structures, and any reports of run-on or run-off problems.

4.2.3.4 Gas Control

Facilities to collect and control the migration of landfill gas were typically not installed in Air Force landfills until very recently. Air Force landfills that have been inactive for many years will probably not have a gas collection system. However, the presence or absence of a gas control system should be verified as part of the site investigation. If a site inspection or construction records indicate the presence of a gas control system, documentation of how it is constructed will be needed.

4.2.3.5 Leachate Control

Collection of landfill leachate was not mandated in landfill designs until the implementation of RCRA Title C and Title D regulations in 1987 and 1991 respectively. Leachate collection and control are typically not present in Air Force landfills because they were built before the advent of these regulations. However, the presence or absence of a leachate collection and control system should be verified as part of the site investigation. If leachate collection and control is present, the results from historical sampling will be valuable to estimate the impact of the leachate on groundwater quality.

4.2.3.6 Groundwater Monitoring

EPA regulations now require that all existing solid waste landfills have a groundwater monitoring system in place to determine if landfill leachates are contaminating the underlying aquifer. The groundwater monitoring system must be capable of yielding representative samples from the uppermost aquifer. In addition, the groundwater monitoring system must include wells that provide representative background water-quality samples.

For many Air Force landfills, a groundwater monitoring network of wells is already in place at the site. Historical groundwater data obtained from these wells should indicate whether groundwater contamination is coming from the landfill and the magnitude of contamination. This information may be available from previous RI/FS studies. If no groundwater monitoring is installed at the landfill site, an initial assessment of groundwater contamination may be possible based on data from wells at other nearby sites.

The analytical parameters of interest for characterizing groundwater, leachates, and soil contamination from an Air Force landfill are listed in Table 9. Note that the parameters listed include the same analytical parameters recommended by AFCEE for characterizing an aquifer except for arsenic, as shown in Table 10. Table 11 lists additional analytical parameters to consider if military-specific wastes (e.g., explosives, munitions) may have been disposed of in a landfill at the site.

4.2.4 Climate

Detailed information about the climate at the site will be needed for the design of a landfill cover. Precipitation (rain, snow, and sleet), solar radiation, temperature, and wind are the main climatic factors that affect landfill covers. Precipitation amounts, of course, have a direct bearing on infiltration of water into the cover and, potentially, into the buried waste. Climatic factors also strongly influence transpiration by plants, which acts to reduce infiltration. Soil erosion will be directly affected by factors such as precipitation and wind.

It is important to note that the commonly reported annual precipitation amounts do not provide sufficient information by which to evaluate a site. Seasonal and daily variations are important considerations. For example, if precipitation is seasonally distributed such that the majority falls during the period when cover vegetation is dormant, the potential for infiltration is much greater than if the precipitation falls mainly during periods of active growth. In some areas of the United States, snowpack accumulates during the winter months and then melts during a relatively short period in the spring. At this time, ET may be low and the ground not thawed; both circumstances will impact infiltration rates.

Typically, the actual design of the landfill cover or other remediation will be carried out by a contractor. Therefore, it may not be necessary for the RPM to obtain detailed climatic data but rather to verify that the design contractor uses climatic data appropriate for the landfill site cover design. Suitable climate data may be obtained from the following sources:

- National Climatic Data Center (NCDC), NOAA, Federal Building, Asheville, NC 28801, (704) 259-0682
- Hydrosphere, 1002 Walnut, Suite 200, Boulder, CO 80302, (800) 949-4937
- EarthInfo Inc., 5541 Central Avenue, Boulder, CO 80301, (303) 938-1788

Table 9. AFCEE Analytical Protocol for Landfills

Expected Contaminants: Metals, petroleum fuels (jet propulsion fuel, aviation gasoline [AVGAS], gasoline, diesel fuel), volatile and semivolatile organics, pesticides, polychlorinated biphenyls (PCBs)

Recommended Analyses		
	Methods [6]	
Parameter	Water	Soil
Conductance (field test)	SW9050	N/A
pH (field test)	SW9040	SW9045
Temperature (field test)	E170.1	N/A
Total dissolved solids (TDS)	E160.1	N/A
Total suspended solids (TSS)	E160.2	N/A
Inorganic anions	SW9056	N/A
Total petroleum hydrocarbons (TPH) (volatile) [1]	SW8015 (modified)	SW8015 (modified)
Total petroleum hydrocarbons (TPH) (extractable) [1]	SW8015 (modified)	SW8015 (modified)
Volatile organics (aromatic and halogenated)	SW8260A [2]	SW8240B [3]
Semivolatile organics	SW8270B	SW8270B
Chlorinated pesticides and polychlorinated biphenyls (PCB)s	SW8080A or SW8081	SW8080A or SW8081
Metals Screen [4]	SW6010A	SW6010A
Mercury [4]	SW7470A	SW7471A
Lead [4]	SW7421	SW7421
Selenium [4]	SW7740	SW7740
Toxicity Characteristic Leaching Procedure (TCLP) [5]	N/A	SW1311
Moisture	N/A	SW846 (3550)

1 The appropriate state-approved method must be used.
2 The GC methods SW8010B (halogenated volatile organics) and/or SW8020A (aromatic volatile organics) may be substituted for GC/MS method SW8260A if the scope of the testing includes only a limited number of analytes that are included in the target analyte lists for these GC methods.
3 Method SW8240B should be specified for determining volatile organic chemicals (both halogenated and aromatic) in soils unless state standards necessitate a method having lower detection limits be used. If this is the case, specify methods SW8010B for halogenated volatile organics and SW8020A for aromatic volatile organics.
4 Analyze water samples for both dissolved and total recoverable metals (two separate samples must be taken).
The sample to be analyzed for dissolved metals must be field-filtered through a 0.45-micron filter after collection and before preservation.
If lower quantitation limits for chromium are required to meet a regulatory standard, specify method SW7191 for chromium. If speciation of chromium is required, also specify method SW7196A for hexavalent chromium.
Positive results for antimony and thallium by method SW6010A should be confirmed by methods SW7041 and SW7841, respectively.
5 TCLP may be required by regulatory agencies to determine leachability of contaminants from the soil.
6 Methods designated with SW are EPA solid waste analysis methods (SW-846) and methods designated with E are EPA wastewater analysis methods.

From: AFCEE, "Environmental Analytical Protocols: A Program Manager's Survival Guide", Version 1.1, page 3-4, August 1997 [60]

Table 10. AFCEE Analytical Protocol for Aquifer Characterization

Expected Contaminants: Solids, inorganic anions, and metals

Recommended Analyses		
	Methods[2]	
Parameter	Water	Soil
Conductance (field test)	SW9050	N/A
pH (field test)	SW9040	N/A
Temperature (field test)	E170.1	N/A
Total dissolved solids (TDS)	E160.1	N/A
Total suspended solids (TSS)	E160.2	N/A
Inorganic anions	SW9056	N/A
Metals Screen[1]	SW6010A	N/A
Arsenic[1]	SW7060A	N/A
Lead[1]	SW7421	N/A
Selenium[1]	SW7740	N/A
Mercury[1]	SW7470A	N/A

1. Analyze water samples for both dissolved and total recoverable metals (two separate samples must be taken).
   The sample to be analyzed for dissolved metals must be field-filtered through a 0.45 micron filter after collection and before preservation.
   If lower quantitation limits for chromium are required to meet a regulatory standard, specify method SW7191 for chromium. If speciation of chromium is required, also specify method SW7196 for hexavalent chromium.
   Positive results for antimony and thallium by method SW6010A should be confirmed by methods SW7041 and SW7841, respectively.
2. Methods designated with SW are EPA solid waste analysis methods (SW-846) and methods designated with E are EPA wastewater analysis methods.

From: AFCEE, "Environmental Analytical Protocols: A Program Manager's Survival Guide", Version 1.1, page 3-10, August 1997 [60]

Table 11. AFCEE Analytical Protocol for Munitions Disposal Areas

Expected Contaminants: Explosives

Recommended Analyses		
	Methods[1]	
Parameter	Water	Soil
Explosive residues	SW8330	SW8330
Moisture	N/A	SW846 (3550)

1 Methods designated with SW are EPA solid waste analysis methods (SW-846).

From: AFCEE, "Environmental Analytical Protocols: A Program Manager's Survival Guide", Version 1.1, page 3-11, August 1997 [60]

4.2.5 Regulatory Status

Currently operating landfills at Air Force bases are subject to their states' landfill regulations. However, there are few operating landfills on bases today, so the closure of base landfills is generally conducted under the DOD's Environmental Restoration Program, following the CERCLA process, under which the RCRA and state regulations are considered as ARARs.

Each Air Force base is in a unique regulatory environment. The specific state regulations, the exact relationship between the federal and state regulators, and the priorities and concerns of the public make each landfill closure decision a singular process rather than a routine regulatory exercise. Understanding this from the outset will allow the RPM to guide the process to a technically sound, protective, and cost-effective closure decision.

To understand the regulatory status of the site, the RPM must first determine and/or verify whether the landfill remediation will be conducted under RCRA or CERCLA. In addition, base records and study reports about the site should be searched to determine if there have been reports of contamination emanating from the site, and if so, has a notice of violation (NOV) been received from the state or EPA.

4.2.6 Closure Process Status

There may be many steps in the closure of a landfill site. The important considerations regarding the site's status in the closure process are to assess what has been done, what is programmed and under contract to be done, and what is left to be programmed and contracted. Consider the following:

- Are there remediation activities already programmed or under way?
- Are there regulatory actions under way that initiate already defined remediation activities?

The answers to these questions may avoid a duplication of efforts and keep the project moving toward the remediation goal.

4.3 Available Soils

Large quantities of soils will be needed if a new landfill cover will be constructed at the site. Different cover designs require different soil types, thus the availability of suitable soils should be investigated. A good indication of the soils available near the landfill site may be obtained from a state soil survey or from soil survey maps of the area developed by the USDA. The USDA soil survey maps are available for many areas on the Internet from the National Soil Data Access Facility (see Appendix E).

The soils used for various layers in the cover will require specific engineering and agronomic properties. Sampling and analysis of the available soils will be necessary to verify that the soils possess the required agronomic properties and to obtain soil property data for cover design. Table 12 lists the soil data typically required.

Table 12. Required Soil Data

Analysis	Reference
Volume and Distribution of Soils to be Used	NA
Typical Agronomic Properties • Available water capacities/moisture characteristic curves • Saturated hydraulic conductivity • Particle size distributions • Nutrient analysis, CEC, organic carbon, pH, salinity	 Ref. #34, Chapter 36 Ref. #34, Chapter 28 Ref. #34, Chapter 15 Ref. #8, Chapters 14, 16, 32, 34, 38, 40
Typical Engineering Properties • Atterberg Index and classification tests • Moisture-density (Proctor tests) • Saturated hydraulic conductivity • Particle size distributions	 Ref. #2 Ref. #3 Ref. #34, Chapter 28 Ref. #34, Chapter 15

4.4 Site Hydrogeology

The geology of the site and the lithology of geologic units between the waste and the groundwater table are important considerations. The distance between the bottom of an unlined landfill and the water table, and the lithology of the intervening soils and rock, are important factors in determining the probability that groundwater has been or may be contaminated. If the landfill has no liner but rests on highly impermeable bedrock, shale, or clay, and if the depth to groundwater is great, then an older Air Force landfill may pose little threat to groundwater. At the other extreme, if waste is actually in contact with groundwater, there may already be groundwater contamination, and the required remediation efforts for the landfill may be extensive.

The important information to obtain is the characteristics of the soils above and below the water table, seasonal fluctuations in the depth to the water table, direction and rate of groundwater movement, and any indications that perched water layers may exist within the landfill. Some or all of this information may be available from previous studies at or near the landfill site. Missing information may be determined in the field by installing groundwater piezometers or monitoring wells.

4.5 Monitoring Wells

Additional groundwater and soil gas monitoring wells may be needed to supplement existing information or provide additional information about the nature and extent of contamination. Before any new monitoring wells are installed, the RPM should initiate a thorough search of site records to document the existing wells at the site including well installation details. In addition, the RPM should also locate and document any existing wells on the base that might serve as references for background groundwater conditions.

If additional monitoring wells are required, they should be installed in accordance with ASTM Standard D5092-90 "Standard Practice for Design and Installation of Ground Water

Monitoring Wells in Aquifers" [1] or the well installation standards in Section 5.6 "Monitoring Well Construction" of the AFCEE Model Field Sampling Plan [61]. The AFCEE document may be obtained from AFCEE's Internet web page (see Appendix E).

4.6 Sampling and Analyses

Collection and analysis of groundwater, soil, and soil gas samples may be required to supply additional information about the nature and extent of contamination at the landfill site. If a stream or lake is nearby, surface water and sediment samples may also be required to determine if the landfill is affecting environmental quality. Before a new sampling and analysis program is begun, the RPM should initiate a thorough search of site records to document whether there is an existing monitoring program at the site, what analyses have been performed, and if the existing monitoring program can be modified or expanded to obtain the needed data.

If additional sampling and analyses are required, they should be performed in accordance with the following standard protocols:

- Groundwater sampling should follow the procedures described in Section 6.1—"Sampling Procedures"—of the AFCEE Model Field Sampling Plan [61].
- The analytical protocol for landfill groundwater monitoring is summarized in Table 9. The methods are described in the AFCEE document "Environmental Analytical Protocols: A Program Manager's Survival Guide" [60].
- Soil gas sampling should be done in accordance with ASTM Standard D5314-93 "Standard Guide of Soil Gas Monitoring in the Vadose Zone" [1] or as described in Section 5.4 "Soil Gas Surveys" of the AFCEE Model Field Sampling Plan [61].

Both the Model Field Sampling Plan and the Environmental Analytical Protocols may be obtained from AFCEE's Internet web page (see Appendix E). Sampling and analysis quality assurance should follow the recommendations in the AFCEE Model Quality Assurance Project Plan (QAPP) [62], which is also available from AFCEE's Internet web page (see Appendix E).

4.7 Information Requirements Summary

The amount of information required to take a landfill remediation from start to finish is extensive. Table 13 summarizes the information that will be needed by various parties during the landfill remediation effort. Many of these items were discussed in the previous sections. The rest of the items are used in making decisions regarding the applicability of the EPA presumptive remedy to the site. The decision process will be handled with the aid of the *Decision Tool for Landfill Remediation* [44], described in Section 5.1.1, and the information requirements listed in Table 13 are keyed to the use of that tool.

Table 13. Landfill Remediation Information Requirements

Topic	Topic
Site History	**Waste Deposits**
Operating history of the landfill	Size and volume of landfill contents
Disposal periods	Waste fill age
Waste sources, types, and quantities	Waste fill types & composition
Area and Regional	Waste fill lateral extent
Topography of the area	Waste thickness
Nearby residential areas	Waste moisture content
Nearby commercial & industrial areas	Waste decomposition rate
Surface water drainage patterns	Thickness of waste below water table
Springs and seeps	**Geology**
Nearby wells and water intakes	Major regional geological units
Municipal/industrial wells & water intakes	Depth to bedrock
Wetlands, floodplains, and wildlife habitats	Site soil lithology (soil horizons)
Area Climate	Underlying natural soil layers
Wind velocities	Elevation of underlying natural soil
Temperature and solar radiation	Site soil moisture content
Precipitation and peak storm event	Site soil pH
Frost depth	Site soil erosion rate
Evapotranspiration rate	Site soil grain size
Site Conditions	Site soil Atterberg limits
General condition of the landfill	Site soil permeability
Landfill surface contours (e.g., slopes)	Permeability of base soil (below waste)
Ground surface and drainage features	**Hydrogeology & Surface-water Hydrology**
Areas/locations of known/suspect hotspots	Groundwater recharge and discharge areas
Locations of known potential hazards	Irrigation canals and supply
Contaminant seeps	Location of surface water bodies
Landfill slope stabilities	Surface water level measurements
Landfill total settlement rate	Seasonal surface water fluctuations
Landfill differential settlement rate	Underlying aquifers and perched aquifers
Site & background sampling locations	Usable aquifers, confining layers, fractures
Existing onsite wells, borings, test pits	Water-table elevations and depth
Well construction data	Groundwater flow direction and gradient
Leachate hydraulic head level	Groundwater flow through waste
Vegetation on site	Hydraulic conductivity of shallow aquifer

Table 13. (Concluded)

Topic	Topic
Contaminants	**Existing Cover**
Landfill gas and hotspot emissions	Physical condition of existing cover
Leachate outbreaks	Aesthetics of the cover
Leachates in wastes, seeps, and streams	Cover area
Leachate contamination from hotspots	Cover thickness
Gas	Cover surface slopes
Landfill gas production rate	Cover stability
Gas quantity	Cover soil characteristics
Subsurface landfill gas migration	Cover's ability to provide erosion control
Offsite landfill gas migration	Cover's ability to control infiltration
Sampling & Analyses	Cover's resistance to freeze/thaw damage
Site groundwater sampling data	Cover's ability to reduce gas emissions
Background groundwater sampling data	Cover's resistance to oxygen intrusion
Groundwater chemistry	Cover's ability to control odors
Landfill gas composition	**Land Use Plans**
Landfill gas moisture content	Land use/reuse plans
Landfill gas temperature	Number of landfills at base/facility
Landfill gas concentrations in ambient air	**Regulatory**
Gas concentrations at landfill perimeter	State permit/closure information
Leachate pH	Federal ARARs (e.g., RCRA Sub. D or C)
Leachate BOD_5 and COD	State and Local ARARs
Leachate TDS and TSS	Federal landfill gas ARARs
Leachate phosphorus and nitrogen	State and local landfill gas ARARs
Leachate oil and grease	Federal leachate ARARs
Leachate TCL organics	State and local leachate ARARs
Leachate TAL metals	

5 Remediation Requirements

Landfill sites should be evaluated to estimate risks to human health and the environment. Likewise, the evaluation and selection of remediation alternatives should be based on the performance of each alternative in protecting human health and the environment. Using the RB/PB landfill evaluation ensures a process that minimizes regulatory prejudices for particular technologies and increases the opportunities for applying innovative technologies.

This section provides guidance in determining what actions will be required to remediate a landfill site, establishing performance-based specifications, developing alternatives that may meet the performance-based specifications, and selecting an alternative for design and installation. The *Decision Tool for Landfill Remediation* [44] should be used in conjunction with this section.

The EPA has published written guidance for developing and screening alternatives during remedial investigations and feasibility studies under CERCLA [68]. The same approach is used here for screening and selecting appropriate alternatives for remediating a landfill site.

5.1 The Presumptive Remedy

The EPA has adopted presumptive remedies for common site categories based on historical patterns of remedy selection and the EPA's evaluation of performance data from selected technologies. Presumptive remedies are expected to ensure the consistent selection of remedial actions and to reduce the time and cost required to clean up similar sites by streamlining site investigation and accelerating the remedy selection process. The regulators generally expect that presumptive remedies will be used at all appropriate sites. An analysis of site-specific conditions will indicate whether the presumptive remedy is appropriate at a given site.

The EPA's presumptive remedy for landfills is source containment. Containment of the landfill contents is accomplished through the construction and/or implementation of one or more of the following components of the presumptive remedy:

- Landfill surface cover
- Landfill gas collection and treatment
- Source-area groundwater-control system
- Leachate collection and treatment system
- Institutional controls

It should be understood from the outset that containment does not automatically imply that a landfill cover will be installed. The need for a new landfill cover is based on site-specific conditions. If a cover is appropriate, containment does not imply that a RCRA barrier-type cover is required. In many cases, an alternative design can meet all of the performance requirements while providing significant cost savings, both in the original installation cost and in the long-term cost of cover maintenance.

Applying the presumptive remedy enables streamlining the risk assessment and focused feasibility study (FFS) for the source area that the landfill represents. A streamlined risk assessment for a municipal landfill focuses on the most obvious problems at the landfill (e.g., landfill contents, landfill gases, groundwater contamination, and leachate) to provide a clear and quick indication of whether remedial action is warranted at the landfill. The risk assessment is streamlined; it does not include a fully developed, quantitative assessment of the risks associated with all contaminants, exposure pathways, and potentially exposed receptors. Instead, the streamlined risk assessment identifies exposure pathways in the conceptual site model (CSM), explains how the presumptive remedy addresses each pathway, and focuses on assessing risks from any pathways not addressed by the presumptive remedy.

To the extent possible, existing data are relied upon to determine whether the presumptive remedy is appropriate for a landfill rather than fully characterizing the landfill contents. If the data are adequate to assess the landfill, the same data are used to develop a streamlined FFS, which evaluates only the no-further-action alternative and the need for (and likely effectiveness of) each of the four components of the presumptive remedy for the source area. Because most Air Force landfills have already been investigated, little or no additional source investigation should be needed to support this effort unless the available information indicates the need to investigate hotspots. Streamlining the process in this way saves time and other resources that would otherwise be expended to complete a conventional RI/FS or engineering evaluation/cost analysis (EE/CA) for the source area.

The presumptive remedy is likely to be applicable at a substantial number (if not the majority) of Air Force landfills. Thus, determining whether the presumptive remedy is applicable is an important step in the remedial decision-making process for landfills at Air Force bases. The decision to use the presumptive remedy can be for a single landfill or as part of the basewide strategy, depending on nature of wastes, landfill size(s), land re-use potential, public acceptance, and other factors.

5.1.1 Decision Tool for Landfill Remediation

The *Decision Tool for Landfill Remediation* (*Decision Tool*) [44] was developed to provide the Air Force RPM with guidance in determining whether the presumptive remedy is appropriate for a specific landfill and in selecting the necessary components to adequately contain the waste. The *Decision Tool* is presented as a series of 15 decision logic charts with explanatory notes that outline the required thought process. The overall decision process is summarized in one chart. The supplementary charts provide additional detail to illustrate individual steps.

Taken together, the logic charts and notes provide a comprehensive guide through the decision process for landfill remediation. However, not all of these steps and notes will be needed to arrive at a decision for a specific landfill. Following the steps outlined in the summary chart, and referring only to the cited supplementary charts and notes needed in the decision process for that landfill will typically trace a relatively simple path through a limited number of charts and notes. The information items required to make these decisions are listed in Table 13 (see Section 4).

5.2 Beginning the Decision Process

EPA established source containment as the presumptive remedy for landfill sites containing municipal solid waste that are regulated under the *Presumptive Remedy for CERCLA Municipal Landfill Sites* [70]. The municipal landfill presumptive remedy should also be applied to all appropriate military landfills using the guidance in *Application of the CERCLA Municipal*

Landfill Presumptive Remedy to Military Landfills [71]. This directive provides a step-by-step approach to determining when a specific military landfill is an appropriate site for application of the containment presumptive remedy. It identifies the characteristics of municipal landfills that are relevant to the applicability of the presumptive remedy, addresses characteristics specific to military landfills, outlines an approach to determining whether the presumptive remedy applies to a given military landfill, and discusses administrative record documentation requirements.

The remedial decision process for a landfill begins with two primary questions:

- Is remediation warranted at the landfill?
- If so, is the presumptive remedy appropriate for the landfill?

The answer to the first question will provide the justification for either an NFA decision or a decision to remediate the landfill. If there is sufficient evidence to support a decision to remediate, then the answer to the second question will indicate whether the RI/FS and/or EE/CA process can be streamlined through the application of the presumptive remedy for landfills.

The principal objective at this early stage of the decision process is to answer these two questions by relying to the extent possible on existing data and any additional information obtained through a site visit. Little or no additional source investigation should be needed to answer these questions because typically Air Force landfills have already been investigated sufficiently. If obtaining additional data is critical to making these decisions, the scope of the field effort should be limited to obtaining just the minimum amount of information necessary for the decisions.

A conventional RI/FS and/or EE/CA process must be performed if either of the two principal questions cannot be answered with sufficient certainty based on the existing information and the results of limited additional investigation. Likewise, if the available information indicates that remediation is clearly warranted but the presumptive remedy is clearly not appropriate, then a conventional RI/FS and/or EE/CA process must be performed to determine the appropriate remedial and removal action(s). The conventional approach will include a fully developed baseline risk assessment and a fully developed technology-screening step.

5.3 Classifying the Type of Waste

The presumptive remedy is considered appropriate for landfills containing waste typical of a municipal landfill. Therefore, it must be determined whether the waste in a specific military landfill is similar in characteristics to municipal landfill waste or whether other factors show that containment is appropriate. At most Air Force landfills, the wastes should be similar in characteristics to municipal landfill waste, and containment should be appropriate for nearly all Air Force landfills. The decisions leading to classifying the waste and determining whether containment is appropriate are shown in Figure 3 of the *Decision Tool* [44].

5.3.1 Municipal Landfill-Type Wastes

The presumptive remedy is most readily shown to be applicable if the contents of the landfill meet the definition of municipal-landfill type wastes and if the landfill is basically indistinguishable from municipal landfills.

Municipal-landfill–type wastes are characterized as having relatively low risks, except for hotspots. Such wastes are also characteristically impractical to treat because of the large volume and heterogeneity of the wastes.

The presumptive remedy allows treatment of occasional hotspots that contain hazardous wastes. These hotspots may contain industrial hazardous wastes and/or high-hazard military-specific wastes (munitions, chemical warfare agents and training kits, artillery, small arms, bombs, demolition charges, pyrotechnics, propellants, smoke grenades, etc.). Thus, the presence of high-hazard military-specific wastes as hotspots in an Air Force landfill does not preclude the contents of the landfill from meeting the definition of municipal-landfill type wastes.

Further, the low-hazard military-specific wastes (e.g., low-level radioactive wastes, decontamination kits, and munitions hardware) in an Air Force landfill are generally no more hazardous than some industrial wastes found in municipal landfills. Thus, the presence of low-hazard military-specific wastes does not preclude the contents of the landfill from meeting the definition of municipal-landfill–type wastes [71].

If military-specific wastes are present, military-waste experts should be consulted. High-hazard military-specific wastes are extremely dangerous and may possess unique safety, risk, and toxicity characteristics. Caution is warranted if historical records or sampling data indicate that high-hazard wastes may have been disposed of at the landfill. Some high-hazard wastes could present low risk, depending on location, volume, and concentrations. Specialists in military wastes (e.g., Air Force Civil Engineering Support Agency[2]) should be consulted to determine whether the military-specific wastes found are low-hazard or high-hazard.

The contents of an Air Force landfill that contains high-hazard or low-hazard military-specific wastes can still meet the definition of municipal-landfill type wastes if the military-specific wastes do not necessarily pose higher risks than the industrial wastes commonly found in municipal landfills. This determination depends on the volume and heterogeneity of the high-hazard or low-hazard military-specific wastes in the landfill, as well as on their nature.

Municipal landfills characteristically contain lower quantities of hazardous wastes compared to the quantity of municipal wastes. Likewise, an Air Force landfill with contents that meet the definition of municipal-landfill–type wastes will contain lower quantities of hazardous wastes (industrial and/or military-specific) than other wastes.

5.3.2 Landfills Not Meeting Municipal-Landfill–Type Definition

Some Air Force facilities have a relatively high level of industrial activity (e.g., weapons fabrication or testing, major aircraft repair depots). There may be a higher proportion and wider distribution of industrial and/or military-specific hazardous wastes at these facilities. Landfills at these facilities are less likely to have contents that can meet the definition of municipal-landfill–type wastes.

However, the presumptive remedy may also be applicable to a landfill with contents that do not meet the municipal-landfill–type definition if containment can be shown to be the most appropriate remedy for the landfill [71]. For example, site investigation or attempted

[2] The Air Force Civil Engineering Support Agency, Contingency Support Division, Tyndall AFB, Florida, 32403-5319, (904) 283-6410.

treatment may cause greater risks than leaving the waste in place, particularly if high-hazard military wastes (e.g., ordnance) are present in the landfill; containment might be as protective of the environment without these increased risks. Conversely, site-specific conditions (e.g., the presence of a high water table or a sensitive environment) may cause the presumptive remedy to be less suitable than other options.

5.4 Handling Hotspots

The decision to consolidate or treat contaminant hotspots within the landfill is a site-specific judgment. If there is evidence that (1) a principal-threat waste—waste materials that are highly toxic and generally cannot be readily contained—has been placed in the landfill, (2) the approximate locations are known and accessible, and (3) the quantity of hotspot material is small enough to make removal or treatment economically viable, then characterization and/or treatment is warranted. The overriding question is whether the combination of the waste's physical and chemical characteristics and the volume of the hotspot waste is such that the integrity of the new containment system will be threatened if the waste is left in place.

A plan should be developed to excavate and/or treat hotspots prior to implementing the presumptive remedy. However, before committing to a strategy for handling hotspots, a cleanup criterion should be firmly established and accepted by the regulators; otherwise, cleanup to background concentrations might be imposed. If hotspot remediations are not required, the conclusions should be documented that no on-site hotspots amenable to excavation and/or treatment exist, and the presumptive remedy is sufficient to protect human health and the environment.

Hotspots should be treated as unique sites within a landfill. Any additional sampling efforts should be focused on further characterizing the known or suspected hotspot(s) in the landfill. For example, a limited investigation might include one of the following:

- Geophysical and/or soil-gas surveys to delineate hotspots
- Excavating test pits or drilling soil borings to confirm the nature and extent of hotspot(s)
- Collecting and analyzing soil samples to determine the characteristics of the hotspot(s) wastes

A plan should be developed to excavate and/or treat hotspots prior to implementing the presumptive remedy. Excavation of waste material will be required if one of the following options is selected for remediating the hotspot(s) materials:

- On-site consolidation
- *Ex situ* treatment
- Off-site disposal

Note that on-site consolidation does not require treatment because RCRA land disposal restrictions (LDRs)[3] do not apply (see Section 2.1.1).

If excavation of a hotspot is not required or not practicable, then the conclusions should

[3] See 40CFR268—Land Disposal Restrictions.

be documented that, based on the available information, no on-site hotspots amenable to excavation and/or treatment exist, and the presumptive remedy is sufficient to protect human health and the environment.

5.5 Stakeholder Involvement

The community and state regulators should be notified that the presumptive remedy is being considered before drafting an FFS or EE/CA work plan. It is important for all stakeholders (project team, regulators, and citizens' groups) to understand the differences between the presumptive remedy and the usual cleanup process, as well as the benefits of the presumptive remedy process. Frequent, open, and clear communication will often allay suspicions and forestall potential confrontations.

5.6 Focused Feasibility Study and Streamlined Risk Assessment

An FFS should be developed to evaluate the components of the presumptive remedy and the NFA alternative for the landfill. The presumptive remedy requirements should be developed in a site-specific manner. This procedure depends on numerous site-specific factors, including landfill waste type, quantity and age, climate, landfill history and geologic setting, local surface- and groundwater use, and regulatory requirements.

If the NFA alternative is found to be appropriate and acceptable at this point in the process, then this conclusion should be documented. Otherwise, the conclusion should be fully documented that one or more of each of the components of the presumptive remedy is needed and likely to be effective.

A streamlined risk assessment should be conducted to evaluate the complete exposure pathways that the components of the presumptive remedy will not address. A conventional RI/FS or EE/CA should be performed to address any unacceptable risks that might be associated with exposure through these pathways. Otherwise, the conclusion should be fully documented that the presumptive remedy alone will be sufficient to protect human health and the environment from contaminants in the landfill.

5.7 Establishing Requirements

An RB/PB landfill evaluation is a technically based approach to select protective remedial options based on the specific conditions at a landfill. An RB/PB landfill evaluation introduces a process that eliminates regulatory prejudices for a particular technology. Using an RB/PB evaluation will allow the landfill owner to determine the specific technical performance requirements necessary to address all risks at a landfill. After these technical performance requirements are determined and accepted by the regulatory community and the public, any particular landfill remediation scenario that meets them can be selected, including alternative or innovative covers. It is very important that performance requirements be established as soon as possible, and in every case performance requirements should be established before the remediation design is begun.

The *Decision Tool* [44] provides guidance through the regulatory decisions to this point. The next step is to determine the specific *performance requirements* of each action that must be taken to address the risks identified, including the following:

- NFA designation if no significant risks were identified
- Cover requirements to eliminate direct contact
- Limitation of infiltration to control leachate generation
- Collection and/or treatment of gas, if necessary
- Control of groundwater contamination

Table 14 provides a checklist of performance-based requirements that address the various risks that a landfill might pose. The selection of performance requirements should address all risks in the CSM.

An important goal for landfill covers is to minimize percolation into the waste. The common assumption with conventional covers is that they are impermeable although this is almost never true. Attempts to establish a requirement for infiltration control require clear thinking, and a requirement for zero percolation into the waste is clearly unachievable. The following should be considered when selecting performance-based requirements for the landfill cover:

Table 14. Performance Requirements Checklist for Landfill Remediation

Site
❒ Restrict access to the site
❒ Minimize the release of odors
❒ Promote surface aesthetics
Cover
❒ Prevent direct contact with landfill contents
❒ Prevent contact with toxic gases
❒ Minimize infiltration into the waste
❒ Promote surface drainage
❒ Control surface run-off
❒ Prevent surface run-on
❒ Minimize surface erosion (wind and water)
❒ Prevent scattering of waste by wind or water
❒ Promote growth of surface vegetation
❒ Provide freeze/thaw protection to cover layers
❒ Protect against root intrusion into the waste
❒ Protect against animal intrusion into the waste
Landfill Gas
❒ Collect/channel landfill gas
❒ Dispose of landfill gas
Leachate
❒ Collect and remove leachate
❒ Treat or dispose of leachate
Groundwater
❒ Minimize groundwater contact with the waste
❒ Control groundwater flow through/under the site
Other
❒ Other (Site-specific) ____________

- Estimates of current and past infiltration rate
- Estimates of total past infiltration
- Current or possible groundwater contamination
- Age of the waste
- Distance to receptors of groundwater contaminants and travel time
- Natural attenuation of contaminants in vadose soil and groundwater
- Whether or not the groundwater can be used as a water supply

After performance requirements have been established for a particular remedial action, any remedial alternative meeting those requirements may be selected and applied at that landfill. This process eliminates the need to follow the classical ARARs approach to determine closure requirements and allows the owner to select the most technically sound and cost-effective alternative to address the risk at a particular landfill.

5.8 Selecting Remediation Components

The *Decision Tool* [44] considers the need for each of the containment components individually. If a particular component is not required to meet the performance requirements, this fact should be fully documented.

5.8.1 Landfill Cover

Construction of a new landfill cover is likely to be needed if the existing cover is insufficient to meet site-specific requirements to prevent surface-water infiltration, prevent direct contact with the landfill contents, and/or control surface erosion. A new cover may consist of any of the following that meet the requirements:

- Enhancement of the existing cover (e.g., regrading and/or revegetating existing fill on a landfill in an arid climate or on a landfill in which a substantial portion of the contents lie below a water table that cannot practicably be lowered)
- Alternative covers, such as the ET cover
- Conventional single- or double-barrier cover

5.8.2 Landfill Gas Collection and Treatment System

A gas collection and treatment system will ordinarily not be required for remediation of a landfill unless the site-specific remediation requirements include specific objectives that will not be met through the other presumptive remedy components selected for the landfill.

A passive landfill-gas venting system may be needed to achieve one or more of the following requirements at a specific landfill:

- Reduce human health risks associated with uncontrolled landfill gas emissions
- Prevent pressure buildup under the landfill cover, which can damage barrier layers and/or the overlying vegetative cover
- Reduce the potential for uncontrolled gas emissions and/or pressure buildup at landfills in which the wastes have a high content of organic matter

An active gas collection and treatment system may be required if one or more of the following conditions applies:

- Landfill gas may migrate from the landfill and accumulate in existing or planned buildings and result in an explosion and/or inhalation hazard.
- Reuse plans include public access to the landfill after closure.
- Excessive odors must be controlled.
- Compliance with ARARs is likely to require active gas collection, and waivers of these ARARs are unlikely to be granted.

5.8.3 Groundwater-Control System

One or more of these systems may be needed to control contaminated groundwater if any of the following conditions applies:

- Lateral infiltration of upgradient groundwater through the landfill contents can release a significant amount of contaminants into downgradient groundwater
- Infiltration of surface water through the selected cover can leach contaminants from the landfill contents into the groundwater
- Contaminated groundwater exists from past leaching of the wastes and poses a significant threat to human health or the environment

The type of groundwater control system(s) selected will depend on which of these conditions applies and upon site-specific factors.

5.8.4 Leachate Collection and Treatment System

A leachate collection system is a possible presumptive remedy component at a landfill where leachate samples from the landfill perimeter or landfill contents contains contaminants of potential concern (COCs). Selecting a leachate collection and treatment system under these circumstances would depend on whether or not a COC in the leachate is likely to contaminate groundwater or surface water and as a result exceed an ARAR. However, neither sampling nor treatment of leachate from Air Force landfills may be practical because Air Force landfills typically have neither liners nor leachate collection systems.

5.8.5 Institutional Controls

Institutional controls—such as deed restrictions, fencing, or sign posting—can constitute a useful component of the presumptive remedy and can be used to supplement and help protect the long-term integrity of the engineering components of the presumptive remedy. Institutional controls should be considered, especially if one or more of the following remediation requirements apply to a specific landfill:

- Preventing development of the landfill surface in the future
- Protecting the surface cover from erosion
- Preventing trespassing
- Reducing or preventing exposure to landfill gas emissions
- Preventing the use of the groundwater beneath the landfill
- Reducing liability

6 Alternatives Development and Selection

This section describes the development of landfill remediation alternatives and the comparative analysis of those alternatives that lead to selection of the final landfill remediation.

6.1 Alternatives Development

The components of a landfill remediation can usually be assembled in several different ways that will meet the performance requirements previously set forth. The choices of component combinations may be as simple as comparing a conventional barrier cover with gas collection system to an alternative cover, such as the ET cover. Various scenarios can be assembled from the components indicated from the Decision Tool logic. In every case, "No Further Action" will be included in the list of alternatives.

Presumptive remedy components should be combined so that the assembled components form an alternative that meets all of the performance requirements for the site. Each component selected should be designed to be both an integral component of the overall presumptive remedy and compatible with the likely overall final remedy. Innovative technologies should be considered when they meet the performance requirements and offer the potential for either superior performance and/or lower costs while meeting the goal of protecting human health and the environment from contaminant releases. The final remedy—which typically will include the presumptive remedy components selected in combination with other remedial and removal actions—must ultimately be shown to address all complete exposure pathways and COCs for both human and ecological receptors potentially exposed to the COCs.

6.2 Alternative Analysis Criteria

In *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* [68], EPA describes the feasibility study as a three-step process—development of alternatives, screening of alternatives, and detailed analysis of alternatives—leading to final selection of the recommended remediation. Alternatives for remediation are developed by assembling combinations of technologies that address contamination site-wide or within an operable unit. In the screening analysis, each combination of technologies is evaluate based on effectiveness, implementability, and relative cost to select viable alternatives for detailed analysis. The detailed analysis is then used to select the method of remediation.

For most CERCLA sites, a broad range of technologies may be applicable. Applying the presumptive remedy to a landfill site, however, limits the list of component choices to a relatively narrow range of technologies. As a result, the CERCLA screening analysis—typically done to narrow the list of technologies considered at the site—is not necessary. Instead, the detailed alternatives analysis, required by CERCLA, is used to rank the alternatives and then to select the site remediation [68][69]. During the detailed analysis, the alternatives are evaluated against the following nine specific criteria and their individual factors, each is considered individually and is equally weighted for importance:

Threshold Criteria

1. Overall protection of human health and the environment
2. Compliance with ARARs

Balancing Criteria

3. Long-term effectiveness and permanence
4. Reduction of toxicity, mobility, or volume through treatment
5. Short-term effectiveness
6. Implementability
7. Cost

Modifying Criteria

8. State acceptance
9. Community acceptance

More information about all of the criteria, including a comprehensive list of subcriteria, can be found in Chapter 6 of *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* [68]. For the purpose of this discussion, the evaluation criteria have been divided into three groups based on the function of the criteria during remedy selection and are described in the following sections.

6.2.1 Threshold Criteria

The threshold criteria relate to statutory requirements that each alternative must satisfy in order to be eligible for selection. The two threshold criteria are as follows:

- **Overall protection of human health and the environment—**Each alternative is assessed, as a whole, on how well it achieves and maintains protection of human health and the environment. Consideration should be given to the manner in which site risks identified in the CSM are eliminated, reduced, or controlled through treatment, engineering controls (e.g., containment), or institutional controls.

- **Compliance with ARARs—**Each alternative is assessed in terms of its compliance with ARARs, or if a waiver is required, how it is justified. These include action-specific ARARs related to treatment technologies (e.g., air stripping) and to direct discharge to a POTW.

6.2.2 Balancing Criteria

The balancing criteria are the technical criteria that are considered during the detailed analysis. Each technology identified as being practicable for remediation of the landfill site should be evaluated on each of the following FS balancing criteria:

- **Long-term effectiveness and permanence—**Each alternative is assessed in terms of its long-term effectiveness in protecting human health and the environment after the response objectives have been met. Some aspects of long-term effectiveness include the ability of a cover to maintain its integrity, the ability of groundwater extraction to meet cleanup levels, and the long-term maintainability of leachate or gas treatment systems. The magnitude of the residual risk and adequacy and reliability of controls are also taken into consideration. Because the technologies generally considered practicable for municipal landfill sites will not completely eliminate the hazardous substances at a landfill, long-term management of waste is a critical issue. Complete evaluation under this criterion should include determining the risk posed by the remaining waste.

- **Reduction of toxicity, mobility, or volume (TMV) through treatment—**Each alternative is assessed in terms of the anticipated performance of the specific treatment technologies it employs. Generally, reduction of TMV at municipal landfill sites occurs through treatment of hotspots. However, TMV can also be reduced through treatment of groundwater, leachate, or landfill gas. Factors such as the volume of materials destroyed or treated, the degree to which treatment is irreversible, and the type and quantity of remaining residuals are taken into consideration. Technologies such as surface covers and fencing that provide no treatment do not require evaluation under this criterion.

- **Short-term effectiveness—**Each alternative is assessed in terms of its effectiveness in protecting human health and the environment during the construction and implementation of the remedy and before the response objectives have been met. A significant issue of short-term effectiveness is the effect on the community of truck traffic as large quantities of cover material are hauled to the site. Both noise and potential increases in vehicular accidents must be considered. Other issues such as potential VOC emissions during excavation of hotspots and during construction and operation of onsite treatment systems are associated with worker and community protection during the remedial activities. Also included under this criterion are the environmental impacts resulting from the remedial action itself. To evaluate this criterion, the time required to achieve the response objectives must be determined, including an estimate of time to achieve remediation of leachate and groundwater.

- **Implementability—**Each alternative is assessed in terms of its technical and administrative feasibility and the availability of required goods and services. Also considered is the reliability of the technology, the ability to monitor the effectiveness of the remedy, and the ease of undertaking additional remedial actions, if necessary. Administrative implementability considers the relative difficulty of coordinating and obtaining approvals from various regulatory agencies. Similarly, the administrative implementability of treating leachate or groundwater at a POTW depends on how receptive local treatment plant officials are to accepting contaminated water from the site.

- **Cost—**Each alternative is assessed in terms of its present worth of capital construction and the operation and maintenance (O&M) costs. Costs may be difficult to estimate for groundwater extraction and treatment and for hotspot excavation and/or treatment because the volume of contaminated groundwater and hotspot waste is difficult to estimate accurately. The actual costs should lie within the range of +50 percent to -30 percent of the estimated cost using data available from the FFS [69].

Each of the five balancing criteria represents a significant element of the evaluation process. However, in the case of certain technologies frequently used at landfills, evaluation under some of the five criteria may require less analysis. For example, a clay cover does not reduce TMV through treatment, so the evaluation of a clay cover under this criterion does not require any effort regardless of the site. Even though these criteria do not require additional analysis to evaluate, the basic conclusion will still be important to the alternative evaluation. It should be noted that all alternatives may not need to be evaluated with respect to all of a criterion's subcriteria. The key is to identify any subcriteria by which the alternatives vary significantly and to focus on the evaluation those factors.

Table 15 presents balancing criteria evaluation summaries for the technologies most frequently used at landfill sites. The objective of the table is to present basic conclusions that can be made for each technology in light of each of the balancing criteria. The table also estimates for each technology the level of effort required to evaluate the technology under each criterion. The effort for the analysis (i.e., level of analysis) is estimated as low, moderate, or significant, depending on the technology being considered for inclusion in a particular alternative. The two threshold criteria (overall protectiveness of human health and the environment, and compliance with ARARs) are not included in Table 15 because these criteria are evaluated as the assembled alternatives rather than by component.

6.2.3 Modifying Criteria

The modifying criteria are formally assessed after the public comment period. However, state or community views are considered during the feasibility study to the extent that they are known. The modifying criteria are as follows:

- **State/support agency acceptance—**Each alternative is assessed in terms of the technical and administrative issues and concerns the regulatory agencies may have. This is a criterion that is addressed in the ROD once formal comments are received on the FFS or RI/FS report. However, regulatory agency concerns should be considered earlier in the process to the extent that they are known. Frequently, regulatory acceptance is closely related to compliance with the ARARs.
- **Community acceptance—**Each alternative is assessed in terms of the issues and concerns the public may have.

Communications with federal, state, and local regulators and with the community is initiated during scoping and continues throughout the FFS or RI/FS. Once the preferred alternative has been identified in the proposed plan and the proposed plan has been issued for public comment, these criteria are evaluated. Based on the comments received during the formal comment period, the lead agency may modify aspects of the preferred alternative or decide that another alternative is more appropriate.

Table 15. Evaluation of Technologies Frequently Used at Landfills

Technology	Long-Term Effectiveness and Permanence	Reduction of TMV Through Treatment	Short-Term Effectiveness	Implementability	Cost
Deed Restrictions	Relies on access/development restrictions to manage residual risk. Difficulty in enforcement results in low reliability of controls. Because there is virtually no long-term effectiveness, almost no effort to evaluate.	Not a treatment technology. No effort to evaluate.	No health or environmental impacts during implementation. This criterion is not very important for this technology and will not vary from site to site. Almost no effort to evaluate.	Ability to implement depends on local ordinances. May be difficult if legal requirements are not in place, especially offsite. Owner approval needed for deed restrictions. Important criterion since the ability to implement will vary from site to site. Need to contact state or local authorities. Significant effort to evaluate.	Low cost. Significant effort to estimate cost.
Fencing	Relies on limiting access to manage residual risk from direct contact. Reliability of controls is uncertain. fencing limits access to the site although trespassing is possible. Because there is virtually no long-term effectiveness, almost no effort to evaluate.	Not a treatment technology. No effort to evaluate.	With the exception of physical hazards associated with routine construction activities, minimal health, or environmental impacts during implementation. Almost no effort to evaluate.	Easy to implement. Equipment readily available. Almost no effort to evaluate.	Low cost. Little effort to estimate cost.
Grading/ Revegetation	Minimal reduction of residual risk, may reduce risk from direct contact and reduce leachate formation by controlling runoff. May lessen risk from direct contact. Continued maintenance required to achieve long-term reliability. Because there is virtually no long-term effectiveness, almost no effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Proper health and safety protection may mitigate risk. If risk is quantified, moderate effort to evaluate.	Easy to implement. Almost no effort to evaluate.	Low cost. Little effort to estimate cost.
Soil Cover	Reduction of residual risk from direct contact. With proper maintenance is reliable in long term. May use HELP model to evaluate leachate reduction. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Community impact through increased dust and noise from construction and truck traffic if soil is from offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Easy to implement. Determine presence of soil nearby. Moderate effort to evaluate.	Low cost. Moderate effort to estimate cost.
ET Cover	Reduction of residual risk from direct contact. Minimizes future leachate formation and groundwater contamination by virtually eliminating infiltration. With proper maintenance is reliable in long term. May use HELP model to evaluate leachate reduction. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Community impact through increased dust and noise from construction and truck traffic if soil is from offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Easy to implement. Determine presence of soil nearby. Moderate effort to evaluate.	Low cost. Moderate effort to estimate cost.

Table 15. (Continued)

Technology	Long-Term Effectiveness and Permanence	Reduction of TMV Through Treatment	Short-Term Effectiveness	Implementability	Cost
RCRA Subtitle D Cover	Reduction of residual risk from direct contact. Reduces future leachate formation and groundwater contamination by reducing infiltration. With proper maintenance is reliable in long term. May use HELP model to evaluate leachate reduction. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Community impact through increased dust and noise from construction and truck traffic if soil is from offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Easy to implement. Need a source of soil that can be compacted to a hydraulic conductivity $\leq 10^{-5}$ cm/s. Moderate effort to evaluate.	Medium cost. Moderate effort to estimate cost.
Single-Barrier Cover	Reduction of residual risk from direct contact. Reduces future leachate formation and groundwater contamination by significantly reducing infiltration. With proper maintenance is reliable in long term. May use HELP model to evaluate leachate reduction. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Community impact through increased dust and noise from construction and truck traffic if soil is from offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Easy to implement. Need a source of clay, which may be difficult to obtain in some regions. Moderate effort to evaluate.	Medium cost. Moderate effort to estimate cost.
Composite-Barrier Cover (RCRA Subtitle C Cover)	Reduction of residual risk for direct contact. Minimizes future leachate formation and groundwater contamination by significantly reducing infiltration. Will last for 20 to 30 years before replacement is needed if properly designed and contained. Greater reliability than single- barrier cover because of redundancy of barriers, although reliability with large differential settlements may be poor. May use HELP model or risk assessment. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk to workers if waste is disturbed. Community impact through increased truck traffic if clay/soil source is offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Synthetic liner requires specialty contractors to assure proper installation. Need a source of clay, which may be difficult to obtain in some regions. Determine presence of clay nearby. Moderate effort to evaluate.	Medium-high cost (depends on size of landfill). Moderate effort to estimate cost.
Capillary Barrier Cover	Reduction of residual risk from direct contact. Reduce future leachate formation and groundwater contamination by significantly reducing infiltration. With proper maintenance is reliable in long term. May use HELP model to evaluate leachate reduction. May be used as part of another cover design. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Inhalation and direct contact risk if waste is disturbed. Community impact through increased dust and noise from construction and truck traffic if soil is from offsite. Need to determine amount of truck traffic and risk from vehicular and construction accidents. Moderate effort to evaluate.	Easy to implement. Determine presence of soil nearby. Moderate effort to evaluate.	Medium cost. Moderate effort to estimate cost.
Excavation Consolidation	Long-term effectiveness same as cover after consolidation. May use a risk assessment. May need significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Disturbance of waste is a risk to workers. Proper health and safety requirements may mitigate risk. Community impacts through volatilization of waste, dust, and increased truck traffic if cover source is offsite. Significant effort to evaluate to determine volatilization risk, amount of truck traffic, and risk from vehicular and construction accidents.	Same as cover chosen, if dewatering of excavation volumes is large, may complicate implementation. Sampling needed to determine extent of hotspot. Significant effort to evaluate depending on extent of RI data.	Medium-high cost (depends on area being considered). Moderate effort to estimate cost.

Table 15. (Continued)

Technology	Long-Term Effectiveness and Permanence	Reduction of TMV Through Treatment	Short-Term Effectiveness	Implementability	Cost
Excavation of Hotspots; Offsite Disposal.	Effectiveness dependent on the type of offsite facility and whether or not there was a significant reduction in risk due to excavating the hotspot area. Significant effort to evaluate if use risk assessment.	Not a treatment technology. No effort to evaluate.	Disturbance of waste is a risk to workers. Community impacts through volatilization of waste, dust, and increased truck traffic. Significant effort to evaluate to determine volatilization risk, release of hazardous waste risk, extent of truck traffic, and risk from vehicular and construction accidents.	Same as cover plus possible added difficulty of excavating waste in water. Difficult to determine extent of hotspot. Need to find hazardous waste landfill with available capacity. Significant effort to evaluate.	Medium-high cost. Moderate effort to estimate cost.
Excavation of Hotspots; Onsite Incineration.	Less residual waste onsite to manage. The reduction in risk will depend on how much of the overall risk posed by the site has been reduced by excavating the hotspot area. Incineration very effective in long-term for hotspot waste. Significant effort to evaluate if risk assessment is conducted.	Treatment to reduce toxicity, mobility, and volume. The significance of TMV reduction will depend on the magnitude of the threat the hotspot area posed. Moderate effort to evaluate.	Possible impacts from disturbance of waste and improper air emissions. No hazardous waste taken through community. Significant effort to evaluate by determining risk from air emissions.	Metals present may still fail TCLP characteristic test. It may be difficult to control air emissions. Sufficient space must be available on site. Significant effort to evaluate.	High cost. Significant effort to estimate cost.
Stabilization	Improved long-term effectiveness over cover alone if used with cover. If used for outlying hotspots without cover will result in some reduction in risk but will not be as effective as excavation by reducing mobility and consolidation under a cover. May not be effective in immobilizing organic contaminants. All waste remains. Need to determine permanence and long-term risk. May be significant effort to evaluate.	Reduction in mobility of contaminants. No reduction in toxicity. Potential increase of waste volume of 10-50 percent. Stabilization may be reversible over time. Significant effort to evaluate.	Significant health and environmental impacts possible because waste is completely mixed. Impacts from odor, dust, and volatiles. Moderate effort to evaluate.	Materials readily available. May be difficult to achieve sufficient mixing in situ to stabilize waste. Need treatability studies to determine feasibility. Significant effort to evaluate.	Medium-high cost. Significant effort to estimate cost.
Subsurface Drains (leachate and groundwater)	Some risk from groundwater remains for a long time until groundwater remediation is complete. If designed as such, may control further migration. Capture zone analysis may be required. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	No significant impacts during implementation. Drains are usually not installed in landfill. Long time needed to achieve cleanup goals. Significant effort required to determine time until cleanup goals are met.	Easy to implement if subsurface is consistent and well-defined. May need modeling to determine feasibility. Significant effort to evaluate.	Low-medium cost. Significant effort to estimate cost.
Groundwater Extraction Wells (leachate and groundwater)	Some risk from groundwater remains for a long time until groundwater remediation is complete. May effectively control further migration of contaminated groundwater migration. Capture zone analysis may be required. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Installation of wells in landfill material may result in impacts to the community and workers from potential VOC emissions. Also, drilling creates potential VOC emissions. Significant effort required to determine time until cleanup goals are met.	Easy to implement if subsurface is consistent and well known. Wells not reliable in fractured bedrock. Significant effort to evaluate.	Low-medium cost. Significant effort to estimate cost.

Table 15. (Continued)

Technology	Long-Term Effectiveness and Permanence	Reduction of TMV Through Treatment	Short-Term Effectiveness	Implementability	Cost
Onsite Water Treatment and Discharge (leachate and groundwater)	Conventional technologies used to treat leachate and groundwater (metals precip., air stripping, GAC, bio-treatment) are proven and reliable as long as O&M is continued and proper disposal assumed. Significant effort to determine influent and effluent concentrations and reliability.	Treatment provides a reduction in toxicity and/or volume depending on the process option selected. There may be residuals left in the form of sludge or spent carbon. Treatment is not necessarily irreversible. Significant effort to evaluate.	If air stripping is used without gaseous control, may be some impacts. Ultimate disposal of water and residuals may have some impact. Time until environmental clean up goals are met depends on extraction. Collection system may have to be operated permanently because there are continued loadings from the landfill. Very difficult to reliably predict when groundwater goals can be met at landfill perimeter. Significant effort to evaluate.	Usually easy to implement and equipment is available. Treatment of leachate and groundwater generally uses conventional, proven technologies. Unusual processes may be more difficult. discharge requires either NPDES permit or meeting substantive requirements of the permit.	Low-medium cost. Moderate effort to estimate cost.
Treatment at POTW	May not be as reliable as onsite treatment since the POTWs typically do not remove all hazardous constituents. Contaminants may accumulate in sludges, and proper disposal may not be assured. Potentially less reliable where leachate is a significant load on small POTW discharging to a small stream. Difficult to determine reliability. Significant effort to evaluate.	Toxicity and/or volume reduction may not be achieved by POTW. However, residuals remain. Significant effort to evaluate.	Transport of water via pipe has potential for negative impacts on the environment via spills, pipe rupture, leaks resulting in infiltration. POTW bypasses through overflows, exposure to POTW workers. Significant effort to evaluate to determine environmental impacts.	Often POTWs refuse to accept water, even if pretreated. Reliability is plant specific. POTW would need additional monitoring to evaluate effectiveness. Significant effort to determine feasibility and find capacity.	Low cost. Significant effort to estimate cost. (Depends on information supplied by POTW.)
Slurry Walls	Difficult to maintain and therefore may not provide long-term reliability. Moderate effort to evaluate because of difficulty to quantify, may be qualitative evaluation.	Not a treatment technology. No effort to evaluate.	If waste is disturbed, may be limited risk to workers or community. Almost no effort to evaluate.	Technical implementability depends on site geologic conditions. Difficult to monitor reliability. Significant effort to evaluate.	Medium-high cost. Significant effort to estimate cost.
Landfill Gas Passive Vents	Not as effective as an active system in controlling offsite migration in the long-term. Primarily protects cover from a buildup of gas and collects gas local to the passive well or trench. Moderate effort to evaluate.	Not a treatment technology. No effort to evaluate.	Protects cover in short-term. May impact the environment and community through gas release. Modeling may be required. Significant effort to evaluate.	Can be installed as part of a new cover or in existing cover. Moderate effort to evaluate.	Low cost. Moderate effort to estimate cost.
Active Gas Collection	Collects gas either through landfill or through subsurface adjacent to landfill. Is effective for long-term collection of gas. With proper disposal, removes most risk from the landfill gas. Modeling may be needed to determine effectiveness. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	May be an impact to workers by drilling through landfill. Moderate effort to evaluate if waste is disturbed.	Fairly easy to implement as part of new cover or existing cover. Able to monitor effectiveness. Moderate effort to evaluate.	Low-medium cost. Significant effort to estimate cost.

Table 15. (Concluded)

Technology	Long-Term Effectiveness and Permanence	Reduction of TMV Through Treatment	Short-Term Effectiveness	Implementability	Cost
Landfill Gas Thermal Treatment (flares)	Effective means of managing collected landfill gas. Treatment levels may vary over time, requiring long-term monitoring. Significant effort to determine reliability and treatment levels.	Reduces toxicity and volume considerably. Treatment is irreversible. Moderate effort to evaluate although not difficult because of irreversibility.	No significant impact during installation. Even with proper operation, may be slight risk to the community depending on the constituents in the gas. Significant effort to evaluate if modeling is conducted.	Easy to implement. May be difficult to monitor effectiveness because of low detection limits needed. Significant effort to evaluate.	Medium. Significant effort to cost.
Removal, Onsite Consolidation of Sediments	Long-term effectiveness affected by cover type used after consolidation. Effectiveness also depends on magnitude of risk reduced through excavation of sediments. Significant effort to evaluate.	Not a treatment technology. No effort to evaluate.	Disturbance of sediments may further contaminate the surface water. Dredging may have impact on wetlands or surface water biota. Sediments are often left in place to protect aquatic life. Significant effort to evaluate if risk is determined.	Technically difficult to implement due to the possibility of dispersing contamination during dredging. Approval for dewatering/rerouting of stream before excavation may be difficult because of environmental impacts. Sampling during removal needed. Feasibility requires significant effort to evaluate.	Low-medium cost. Significant effort to estimate cost.
Compensatory Wetlands	No management of residuals. Only a replacement of damaged wetlands. Effectiveness is not an issue. Almost no effort to evaluate.	Not a treatment technology and no residuals remain. No effort to evaluate.	The construction of a wetland in a clean area will have positive environmental impacts. No impact to community or workers if area is clean. Almost no effort to evaluate.	Complex to implement successfully. Many ecological factors need to be taken into account. Significant effort to determine implementability.	Medium-high cost. Significant effort to estimate cost, if possible.

Adapted from U.S. EPA, Conducting Remedial Investigations/Feasibility Studies for CERCLA Municipal Landfill Sites [69].

7 Landfill Remediation Design

This section provides an overview of important issues that must be addressed during the design of a landfill remediation. The performance requirements must be established and receive agreement from the regulators prior to design (see Section 5.7). The process for designing the remediation components follows a similar path for most landfills, and typically includes some or all of the following steps:

1. Review site data, soil data, and topography
2. Develop a clearing and grading plan for the site
3. Estimate the cover surface slopes required to achieve adequate drainage
4. Hypothesize a cover design based on site remediation requirements
5. Perform computer modeling of the water balance (including deep percolation) for the proposed cover design
6. If computer modeling indicates deep percolation, modify the proposed design and repeat step 5
7. Perform slope stability calculations
8. Complete a structural design of the cover
9. Design the gas collection and treatment system (if any)
10. Design the leachate collection and treatment system (if any)
11. Design the surface drainage
12. Design groundwater control, if needed
13. Complete other site design details

The details of designing the remediation components are not covered here because there are a number of texts already available to which the contractor responsible for the design may refer. The following are recent texts on landfill design that are suggested as references during the design process:

- Koerner, R.M., and D.E. Daniel. 1997. *Final Covers for Solid Waste Landfills and Abandoned Dumps*, American Society of Civil Engineers, ASCE Press, Reston, VA.
- McBean, E.A., F.A. Rovers, and G.J. Farquhar. 1995. *Solid Waste Landfill Engineering and Design*, Prentice Hall PTR, Englewood Cliffs, NJ.
- Oweis, I.S., R.P. Khera. 1998. *Geology of Waste Management*, 2nd Ed., PWS Publishing, Boston, MA.

7.1 Landfill Cover Design Factors

The design of any landfill cover depends on the performance requirements established for the cover and on site-specific factors including climate, hydrogeology, gas production, seismic environment, and plans for reuse of the area. Landfill characteristics that affect cover design include the type of waste deposited, whether or not the landfill has a liner, the age of the landfill, whether the landfill is active or inactive, and whether or not contaminated leachate may reach receptors. Table 16 summarizes how some of these factors impact the performance of specific cover layers.

Table 16. Factors Impacting Final Cover Performance

Layer	Factor
Surface Layer	• Erosion by water and/or wind • Evapotranspiration • Native versus exotic vegetation • Appropriate armoring of side slopes at arid sites
Protection Layer	• Erosion by water • Slope failure due to pore water pressure buildup • Animal burrows • Deep-rooted vegetation
Drainage Layer	• Clogging • Insufficient flow rate capacity • Insufficient drainage layer outlets or capacity
Barrier Layer	• Cracking due to desiccation or freezing • Slope stability • Root penetration • Fractures caused by waste settlement • Creep of all materials
Gas Collection Layer	• Adequate cover over the waste
Foundation Layer	• Adequate strength • Proper grading

Adapted from Daniel and Gross [18]

This section addresses the following items that may affect the design and/or performance of Air Force landfill covers:

- Cover materials
- Water balance and infiltration control
- Erosion control and surface water management
- Slope stability
- Vegetation
- Drainage layer
- Filter design
- Gas collection
- Settlement and subsidence
- Reuse of landfill areas

7.1.1 Cover Materials

Traditionally, the primary material for constructing a landfill cover was soil native to the landfill area. With the promulgation of the EPA's solid waste regulations in the 1970s, this approach changed, and many new synthetic materials are now being used with native or amended soil.

7.1.1.1 Soils

Selection of soil materials for construction of a landfill cover is subject to the availability of an adequate supply of suitable material and the cost of the material delivered to the site. Very large quantities of soil are required to construct a cover. Each acre of landfill cover requires over 1,225 cubic meters (1,600 cubic yards) of soil for each foot of cover thickness. Thus, even a relatively small landfill of 6 hectares (15 acres) may require over 110,000 cubic meters (145,000 cubic yards, or 7,260 truckloads at 20 cubic yards/load) of soil to construct the 1.8 m (6 feet) of soil layers in the RCRA barrier-type cover described in Section 3.2. Obtaining this amount of suitable soil near the landfill site may be a challenge.

To achieve the low permeability required, the barrier layer of a RCRA cover is typically constructed of clay or a mixture of clay and other soil types. The various types of clay minerals are generally classified into three groups as shown in Table 17. Of particular note is the large expansion index associated with montmorillonite clays. Water enters easily between the crystalline layers of the clay lattice structure, and the clay expands or swells significantly. Various montmorillonite-type clays (e.g., bentonite) have been used widely for drilling mud and slurry wall construction—in addition to landfill construction—because the swelling substantially reduces the soil's hydraulic conductivity.

Mixtures of clay and other soils are sometimes employed. Mixtures of 5-15 percent bentonite clay (wt/wt) mixed with sand were shown to have hydraulic conductivities of less than 5×10^{-8} cm/s in the laboratory [40]. A mixture of at least 50 percent clay- and silt-sized particles can be compacted over a wide moisture range to obtain the desired low-permeability. This mixture—and similar soil mixtures—also have a relatively low susceptibility to frost and erosion damage [40].

7.1.1.2 Geosynthetics

The term geosynthetics is a general one that includes GMs, geotextiles, geonets, and geogrids. All of these are proprietary manmade materials designed for geotechnical (earthwork) applications. Geosynthetics are designed for a number of functions including the following:

Table 17. Characteristics of Major Clay Material Groups

Clay Group	Cation Exchange Capacity (meq/100g)	Specific Surface Area (m^2/g)	Expansion Index (dimensionless)
Kaolinite	3–15	10–20	
Sodium-Saturated			0.20
Calcium-Saturated			0.06
Illite	10–40	65–100	
Sodium-Saturated			0.15
Calcium-Saturated			0.21
Montmorillonite	80–150	700–840	
Sodium-Saturated			2.50
Calcium-Saturated			0.80

From McBean et.al [40]

- **Filtration**—to retain soil while allowing the passage of water
- **Transmission**—to enhance lateral drainage (if the geosynthetic is to be used as a drain, it must possess sufficient stability to retain its thickness under pressure, as well as retain high transmissivity)
- **Isolation**—to isolate two constituents from each other
- **Barrier**—to decrease the transmission of water

The functional uses of various geosynthetics are summarized in Table 18. The manufacturers of these materials can provide information about their products designed for specific applications.

Related to the purely geosynthetics are the geocomposites, which are a relatively thin layer of bentonite clay (e.g., ¼- to ½-inch-thick) bonded to a geotextile filter fabric or sandwiched between two layers of geotextile filter. After placement, the geocomposite is wetted to rehydrate the bentonite clay to form a barrier against infiltration. Geocomposites arrive at the site in rolls, which makes them relatively easy to install compared to hauling, spreading, and compacting a thin layer of bentonite clay. However, they are expensive and provide only a thin clay barrier layer.

Experience with geosynthetics in landfill use only spans a period of about 20 years. However, laboratory testing of HDPE GMs indicates that this material might have a service life of several hundred years depending on site-specific conditions [34]. Many of the other materials used to manufacture geosynthetic products (e.g., very flexible polyethylene [VFPE], flexible polypropylene [FPP], PVC) may have similar long service lives. The lifespan of the geosynthetic material will likely be an issue only if the landfill contains chemicals that might damage the synthetic (e.g., solvents) or contains radioactive wastes with extremely long half-lives. Geosynthetics used in landfill covers might be damaged by volatile chemicals in landfill gas.

7.1.2 Water Balance and Infiltration Control

A primary objective of a landfill cover is to minimize the infiltration of water into the underlying waste, and as a result, to minimize the production of leachate that may threaten to contaminate groundwater. The analysis of water movement in cover layers—called water-balance analysis—is used by designers and regulators for the following purposes:

- Compare alternative design profiles and materials
- Understand which water-routing mechanisms are most important in a particular application

Table 18. Functional Uses of Geosynthetics

Geosynthetic Form	Function
Geonets	Used to provide lateral drainage
Geogrids	Used to improve slope stability by reinforcing the supporting soil or preventing deformation
GMs	Used as a barrier to water movement
Geotextiles	Used as a filter to separate fine-grained and coarser granular materials or as reinforcement in a geocomposite
Geomats	Used to prevent erosion of exposed slopes

- Estimate water flow rates for design of the remediation components
- Estimate the quantity of contaminated water (leachate) that may be generated

Only a portion of the water that reaches the ground as rain, snow, or sleet actually infiltrates the surface cover layer. Much of the water may be removed at the surface as runoff or evaporation. A portion of the water that penetrates the surface is removed by vegetative transpiration, and most of the rest may be diverted laterally by a drainage layer incorporated into the cover design. Conventional barriers such as GMs and CCLs, as well as innovative designs such as ET covers, are designed to minimize the amount of infiltrated water that percolates through to the waste. A schematic of this process is illustrated in Figure 10 [34]. Based on the principle of conservation of mass, the water infiltrating a landfill cover's surface must equal the sum of the flows out of the cover plus any change in water stored within the cover, or:

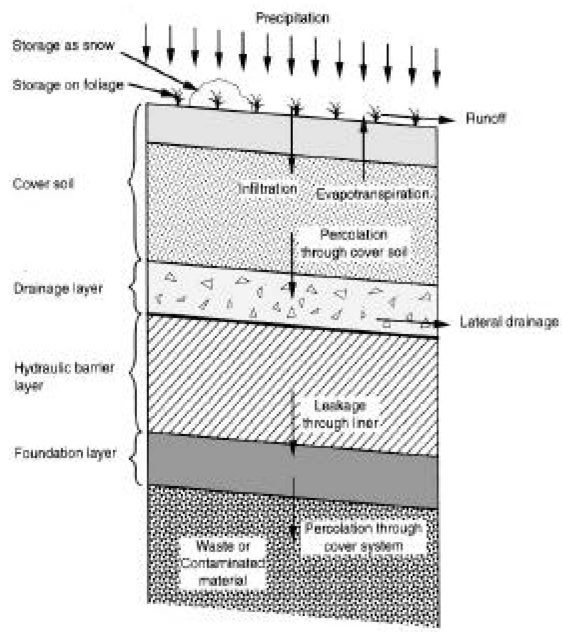

Figure 10. Water Movement Through a Typical Landfill Cover

$$\text{Precipitation} = \text{Run-off} + \text{Evaporation} + \text{Transpiration} + \text{Lateral Drainage} + \text{Percolation into the Waste} + \text{Change in Soil Water Stored}$$

An analysis of each of these streams is the "water balance" that is used to evaluate and design the landfill cover system. The principles of a water balance analysis for a landfill cover are described in detail in recent texts [34][39][40]. The *Hydrology Handbook* [4] is recommended as a reference for detailed explanations of the soil physics applied to each term and for the mathematics for calculating estimated values.

Although textbooks may describe how the water balance analysis can be done by hand, nearly all such analyses today are performed using computer models. The calculations are complex and must use a small time step over a long period (e.g., daily steps over 5 or more years) in order to be meaningful. Since the landfill cover is required to be protective over a long period of time, the design should be based on the most critical event that may be expected to occur in a similarly long period of time (e.g., 30 to 100 years). This most critical event produces a design maximum stress on the cover. A computer handles the large climate databases, generates probable climatic events, and estimates daily landfill cover response over decades in order to identify the expected critical event and evaluate the cover's response to that event.

The computer model historically most often used for landfill cover designs is HELP (Hydrologic Evaluation of Landfill Performance), which was developed by the U.S. Army Corps of Engineers' Waterways Experiment Station under EPA sponsorship [52]. One of the primary functions of HELP—or any other model used in cover design—is estimation of the water balance for the landfill. The model receives input of weather, soil, and other site-specific data, and calculates various algorithms to account for the water balance in each layer of a hypothesized cover design over time.

The model accounts for the effects of water storage on the surface, snowmelt, runoff, infiltration, ET, vegetative growth, soil moisture storage, lateral drainage through a drain layer, leachate recirculation (if any), vertical percolation, and leakage through hydraulic barriers. The HELP model was created to model the hydrologic response of landfills using barrier-layer covers and having a modern double liner at the bottom of the landfill. It places great emphasis on the movement of liquids below the cover surface and was originally tested extensively and refined to produce accuracy in estimating a water balance in the waste, leakage through the bottom liner, and the volume and rate of water collection in the liner drainage system. However, with the emphasis on barrier layers to retard infiltration, the HELP model does not directly model unsaturated flow of water in fine soil and is somewhat less sophisticated in its handling of ET. Clearly, the emphasis in the HELP model was the response of manmade systems and the waste material lying below the soil cover.

The HELP model has also been used to develop the design of leachate treatment facilities for new lined landfills. While many feel the HELP model has been a valuable tool in predicting leachate generation rates, others note that it can be misused to demonstrate whether or not leachate will be generated during the early period of landfill operations when the landfill is uncovered [34]. The modeling results for leachate production during that time depends almost entirely on the assumptions made by the modeler about the initial moisture content of the waste (whether or not it is near its field capacity), and this type of information is not usually known with good accuracy. Thus, in one sense, one could get just about any answer from HELP that one wants, depending on the key assumption about the initial water content of the waste. Because the Air Force is no longer constructing new landfills and the existing landfills are typically older, inactive facilities, it is unlikely that this potential misapplication of the model will arise.

In its favor, the HELP model is well known by the regulatory community, which has accepted its use to design new landfill facilities. Against this, however, is mounting evidence that HELP is not accurate in a number of circumstances. Fleenor and King [22] found that although the HELP model is effective in simulating water flux through a barrier layer in humid areas, it has a tendency to overestimate water flux for landfills in arid and semi-arid climates. A field-scale study of earthen landfill final covers revealed that HELP underpredicted runoff and overpredicted percolation [9]. They also pointed out that the use of HELP to evaluate and compare conventional barrier covers against innovative covers, particularly in arid or semi-arid environments, could lead to the wrong decision. HELP was shown to underestimate surface runoff in a study of the Fresh Kills Landfill in New York [31], and other reports showed that HELP sometimes predicted too much and sometimes too little percolation into the waste [48].

Recently, other models have been used to evaluate percolation through landfill covers; these models include the Unsaturated Soil Water and Heat Flow (UNSAT-H) Model [19], the Environmental Policy Integrated Climate (EPIC) model [78], the Groundwater Loading Effects from Agricultural Management Systems (GLEAMS), and Water Balance Analysis Program (MBALANCE) model. The EPIC and GLEAMS models were developed to solve water-balance problems in agriculture that are similar to those found in landfill covers. EPIC uses the Soil Conservation Service (SCS) Curve Number model for estimating infiltration. Both of these models take a more sophisticated approach to ET, and may be more appropriate for use where ET is a primary mechanism for minimizing infiltration. The UNSAT-H model has been used to design conventional, as well as capillary- and dry-barrier type, covers in arid climates. UNSAT-H models infiltration, soil water storage, and water movement in fine soils using a numerical solution to the Richards equation. This is a theoretically sophisticated approach for modeling water movement in soils [4], which makes UNSAT-H popular for designing capillary barriers and other alternative cover designs. UNSAT-H also incorporates a numerical estimate for vegetative transpiration, which is necessary for modeling vegetative cover designs.

The requirements for hydrologic design of the ET cover and other vegetative cover designs are different from those for conventional covers. Estimates of soil water storage and water movement through the cover (deep percolation) are of particular concern. EPIC is a comprehensive model with sophisticated handling of ET and demonstrated ability to estimate deep percolation with good accuracy, which has been extensively tested for water balance estimates [28]. Thus, EPIC is well suited to meet the requirements for designing covers that depend on ET as a principal water removal mechanism.

An extensive discussion of models is beyond the scope of this document, but it is apparent that HELP in its present form will not suffice for every type of cover design. Nevertheless, it remains the model most familiar to regulators and practicing engineers, and so it remains an important influence in landfill design. The HELP model and its documentation are free and available for downloading from the Army Corps of Engineers Waterways Experimental Station. The DOS version of UNSAT-H is also available for free download from the author (see Appendix E).

Even though the HELP model and other water-balance models used to predict the performance of covers in terms of water percolation are powerful tools, they contain numerous simplifying assumptions. Many of these assumptions have been inadequately verified by field data. Different models may produce widely ranging estimates of water infiltration under site-specific conditions. As a result, Koerner and Daniel [34] suggested that the main value of these models may be to compare alternative designs using different cover configurations and materials. A project sponsored by the Air Force is under way to evaluate HELP, EPIC, and one or more other models against long-term field measurements to determine the accuracy of each model [46]. The results of this study may finally demonstrate which model is appropriate for a given set of site conditions, and may also indicate areas for further refinement of individual models.

7.1.2.1 Cracking in Conventional Clay Cover Barrier Layers

Compacted clay barrier layers may fail due to cracking of the clay; as a result, water can pass through the cracks into the underlying waste. Cracking results from any of three primary causes:

- The clay barrier layer freezes and cracks result from uneven stresses induced by formation of ice crystals and lenses.

- The clay barrier layer dries out completely (desiccates) and stress cracks form in the clay due to shrinkage during drying.
- Differential settling of the waste may produce cracks.

Potential cracking of the clay barrier is of particular concern if the clay is not protected from freezing. This problem is most severe in the northern tier of states where frost may penetrate more than six feet into the ground at some locations. Frozen ground is weak in tension. Therefore, the stresses induced by the formation of ice may result in crack formation at the ground surface and penetrating the cover soils to the depth needed to relieve the tensile stresses. Frozen soil under a constant stress will deform in a viscous manner over time if the stress is not relieved first by cracking. The resulting creep behavior will reduce the tensile stresses over time, but also results in loosening the compaction of the soil and increases its permeability after the soil thaws.

A field test conducted in Germany illustrates the problems that may occur with drying of clay soils [34]. The test included four barrier-cover designs, each of which was covered by 750 mm (30 inches) of topsoil and 250 mm (10 inches) of fine gravel for drainage. The four barriers were built as follows:

- 600 mm (24 inches) of compacted clay
- Composite layer made of HDPE GM with welded seams over compacted clay
- Composite layer made of HDPE GM with overlapping, non-welded seams over compacted clay
- Compacted clay over 600 mm of fine sand over 250 mm of coarse sand and fine gravel to form a capillary barrier

The covers with composite barriers performed well and allowed no percolation. The CCLs performed well for 20 months. However, during a drier-than-normal summer, the clay layers dried. After the dry summer, percolation through the compacted clay was almost ten times the percolation recorded during the previous year. Exploratory excavations revealed that small cracks and plant roots had penetrated the clay. Seven years after the beginning of the experiment, percolation through the compacted clay was almost 200 mm/yr (8 in/yr) and increasing.

Clay barrier layers are typically covered with a sufficient depth of protective soil so that frost does not penetrate to the clay. Either sufficient soil cover or a GM over the clay may maintain a moisture level in the clay sufficient to reduce shrinking and desiccation cracking. However, the clay may dry slowly from the bottom under some conditions even with a GM over the clay. There is no practical way to ensure that a compacted clay barrier will not dry out or crack in the future.

7.1.2.2 Geomembrane Leakage

GMs are difficult to install completely free of flaws. Improved manufacturing techniques have made defects such as pinholes rare, but they do occur. Flaws can be expected, however, from the field installation that may be done under less than optimum conditions. Flaws are generally the result of imperfections in field seaming of the panels, inadequate repairs, or accidental punctures. Therefore, construction quality control is of prime importance if the cover design includes a GM.

Board and Laine [10] found 26 holes in a 4-acre GM liner. They also reported that 69 percent of the holes were found in the seams. In Britain, Crozier and Walker [17] examined 7 GM installations and found holes ranging in size from pinholes to 2-meter gashes. The average number of holes in their study was 5 per hectare (2 per acre). They also discussed a study of 17 leak location surveys in the United States that showed an average of 6 leaks per acre, but ranged as high as 15 leaks per acre. They concluded that GM leak detection surveys should be used to supplement construction quality assurance programs.

7.1.3 Erosion Control and Surface Water Management

Erosion of surface soil from a cover can be a serious problem. Not only can the efficacy of the cover be diminished, but downstream environments can also be adversely affected. One survey indicated 20 percent of the landfills studied were severely eroded, and another 40 percent were moderately eroded [14].

Inadequate drainage to remove water accumulating above barrier layers can cause severe gully erosion, resulting in loss of all cover over the barrier layers. Without appropriate drainage controls, the soil above the hydraulic barrier layers can become saturated, and further precipitation results in large amounts of surface runoff and potentially severe erosion. The affected area may be limited to gullies or encompass several acres [34][75]. Sperling and Hansen [54] describe erosion of a landfill cover and supporting structures even in a semi-arid climate in Canada. The erosion occurred because the drainage system was overwhelmed by a critical rainfall event.

The agricultural community has studied erosion in detail for more than 80 years, and the factors that affect erosion rates are well understood. The most often used model for soil erosion is the Universal Soil Loss Equation (USLE), which is explained in publications by the USDA [66] and McBean et al. [40]. The terms that are incorporated into this equation, however, provide insight into the factors that affect erosion: rainfall energy, soil erodability, length of slope and gradient, and vegetative cover. With regard to landfill design, the most important factors are slope and vegetation. Lower slopes reduce the velocity of runoff and its erosion potential. Shorter slope lengths reduce the volume of runoff. Slopes of at least 2.5 percent are usually incorporated into a cover design to promote surface drainage, prevent ponding, and provide some allowance for settling and subsidence. All landfill slopes are steep enough to require erosion control.

Vegetation provides both the least expensive and most effective erosion control for landfill covers. Living or dead plant material dissipates rainfall energy and controls both water and wind erosion. A cover of native grasses and forbs (broad leafed plants and weeds) provides a self-renewing, natural erosion control system that can function with little or no maintenance for decades or centuries.

A soil cover is most vulnerable to erosion during the time when vegetation is first becoming established after construction is complete. The timing for completion of cover construction, in relation to the growing season of the vegetation planted, is important. If construction is completed at the end of the growing season, fast-growing annual grasses such as wheat, barley, sorghum, or millet should be established. These temporary covers should be left in the undisturbed state, and the permanent grasses should be seeded into the standing stubble. Temporary erosion control, such as through the use of geotextiles, may be considered for small but critical areas [66].

The final landfill surface should be uniformly graded to a minimum slope of 2.5 percent after allowance for settlement to prevent ponding of rainwater in the future. Surface slopes greater than 10 percent are sometimes used on landfill surfaces. On landfill surfaces, almost any slope greater than zero has potential for serious water erosion. Hydraulic structures such as benches, diversion terraces, dikes, ditches, check dams, pipes, chutes and waterways are often recommended for erosion control of landfill surfaces [34][39][40]. These types of structures perform their intended purpose if, and only if, they are maintained on an annual or more frequent basis. After a short time, it is unlikely that remediated Air Force landfills will receive the attention required to maintain these structures.

Water erosion is controlled on watersheds up to hundreds of acres in size by native vegetation alone in both humid and dry regions. Studies of natural watersheds and revegetated agricultural land demonstrate that an adequate cover of native grasses will reduce water erosion to near zero. Therefore, it is recommended that water erosion be controlled on Air Force landfills by a properly designed cover of soil and grass. Proper design requires that water not be concentrated by hydraulic structures on the landfill surface. Such a cover will require minimal inspection and repair expense.

Wind erosion and windblown dust may be a problem during construction. An adequate cover of soil with native vegetation growing on the surface will reduce wind erosion to near zero in all climatic zones except deserts, where special measures may be required. In deserts, gravel mixed into the surface soil has adequately controlled wind erosion and should remain effective for decades.

A cover of native grass growing on fertile soil will adequately control both wind and water erosion on nearly all Air Force landfills. Hydraulic structures such as benches, diversion terraces, and chutes become a costly maintenance liability on Air Force landfills and should not be used. Fully vegetated covers will simulate a natural ecosystem and will be self-renewing.

Air Force landfill surfaces are generally smaller in size than typical municipal or commercial landfills and have maximum land slopes of 10 or 12 percent. The requirements for successful erosion control are quite different at these landfills. After establishing an adequate stand of several species of grasses and forbs, erosion by wind and water should diminish to near zero. Structures such as benches, diversion terraces, and chutes are generally not needed and not recommended for covers of this kind. The fully vegetated covers will simulate a natural ecosystem and will be self-renewing.

7.1.4 Slope Stability

A landfill cover may be susceptible to instability from lateral movement, particularly when slopes are steep. The principal ways to improve stability focus on soil water management and drainage (see Section 7.1.6) and strengthening the cover through the use of a retaining system. Specific methods are detailed by Koerner and Daniel [34] and by Lutton [37].

Slope failures on final covers may be caused by three destabilizing agents: weight of the wastes and cover materials, seepage forces caused by water infiltration, and seismic forces. Most cover slope failures are related at least in part to seepage problems [34]. The modes of possible slope failure are slipping of one layer over another along cover layer interfaces, slipping of upper soil layers through weak soil layers, and rotational failures where a segment of the cover system and underlying wastes slide and slump. Physically these failures may be described as follows [34]:

- Cover soil slides off the upper surface of a smooth GM.
- Cover soil with an underlying geotextile of drainage geocomposite slides off the upper surface of a smooth GM.
- Cover soil, drainage materials, and underlying GM slide off the upper surface of the underlying soil.
- Cover soil, drainage materials, and underlying GM slide off the upper surface of an underlying hydrated GCL, particularly if the upper surface of the GCL is woven slit film geotextile.

A report by the California Integrated Waste Management Board [14] presents various analytical techniques for evaluating the stability of covers, and Richardson and Kavazanjian [51] detail techniques to evaluate landfills for seismic risks.

Modern landfills maximize waste thickness to contain the maximum waste volume placed over a given area, which may result in steep cover slopes. Slopes of 3H:1V (ratio of horizontal to vertical) are common, and even steeper slopes of 2H:1V have been used [34]. Steep slopes produce less stable conditions within the cover, but typically Air Force landfills were not constructed with steep slopes. Common barrier materials such as GMs and hydrated GCLs have low interface shear strength and increase the concern about instability. Further, the use of geosynthetics for drainage and gas collection layers creates potential shear planes.

Another source of slope failure is the buildup of seepage forces resulting from a failure of the drainage layer above a barrier layer that results in saturated soil layers. The resulting increase in pore water pressure places additional stress on the soils and a slope failure may result.

Slope-stability stress analyses should be calculated assuming that the soils are saturated. Under saturated conditions, the soils will have the much less shear strength than when they are partially unsaturated. This is especially true of the finer-grained soils such as silts and clays. Thus, if the slope is stable at saturation, it will be stable under all other moisture conditions. However, if the cover slopes contain GMs, the slope stability analysis will require additional attention because the plastic GMs are very slick and the interface between the GM and the soil will not be as strong in shear as the soils alone.

Air Force landfill covers usually have relatively flat slopes, so slope stability is typically a small problem. However, slope stability should be evaluated for all landfill cover designs. Additional guidance on designing for slope stability may be found in documents by the U.S. Environmental Protection Agency [74] and in current textbooks [34].

7.1.5 Vegetation

To reduce erosion and allow transpiration to remove water, nearly all cover designs include the establishment of vegetation on the surface layer. For certain innovative cover designs, such as the ET cover, selecting and establishing vegetation is of critical importance to the ability of the cover to prevent percolation of water into the waste. The establishment of vegetation has both short-term and long-term components. It is important to establish vegetation over newly constructed cover systems because it is most vulnerable to wind and water erosion at that time. Furthermore, the long-term health, viability, and maintenance of the vegetation are paramount because the function of the vegetative layer must be fulfilled for many decades. To encourage the rapid establishment of perennial vegetation, it is important to consider soil type, soil pH, nutrient levels, climate, plant species selection, mulching, and seeding time. Specific recommendations related to these factors have been detailed in the technical literature [34][36][41].

McAneny et al. [39] and Schuman et al. [53] point out several important considerations in establishing effective vegetation on landfill covers:

- Use native species that have been naturally selected to grow in the region.
- Use a mixture of species rather than a single species. If growing conditions become difficult for one species, others may be able to maintain the erosion protection.
- In semi-arid and dry regions, plant annual grain (wheat, barley, etc.) and maintain the standing stubble as cover for young seedlings.
- Plant immediately ahead of the highest expected rainfall probability so that the rain will provide moisture for germination.

Further guidelines for the successful establishment of vegetation on landfill covers may be found in McAneny et al. [39], California Integrated Waste Management Board [14], and Gilman et al. [25]. The final cover design should include recommendations for establishing cover vegetation from the state agricultural extension service or the USDA.

Although grasses and forbs have been the most frequently utilized plants for landfill vegetative covers, critical factors affecting the growth of woody plants at such sites have also been investigated [26]. Generally, the use of shrubs or trees as cover vegetation is inappropriate because their root systems extend to a depth that would normally invade the drainage layer, or the barrier layer if it is low-permeability soil. Trees can also create serious problems if they are blown over, uprooting large masses of soil.

Flower et al. [23] conducted a survey and analysis regarding the problems with vegetative growth at landfill sites throughout the United States. They attributed many of the problems to waterlogged soils and the effects of landfill gas.

In order to support growth of vegetation, the surface soil must retain adequate moisture (but not be waterlogged) even during periods of drought. Sandy soils are inadequate for the surface cover material because they hold insufficient water to support plant growth. The solution is to use soils with adequate silt and clay content in the cover soil layer to retain sufficient moisture and nutrients for plant growth even during drought periods. Loams are recommended, if available.

7.1.6 Drainage Layer

Water that penetrates through the cover soil and is stopped by the barrier layer should be removed laterally by a drainage layer built of highly permeable material. Rapid drainage reduces the hydraulic head on the underlying barrier layer, thus reducing infiltration through the barrier layer. Drainage improves slope stability by reducing pore water pressure. In addition, rapid drainage provides aeration for the plant roots growing in the cover soil. The most common materials used for the drainage layer are sand, gravel, and manmade geosynthetic materials.

Geonets are thin manmade drainage layers that have a grid-like character providing extensive opportunity for flow. McBean et al. [40] give an example of a 4.5-mm (approximately $^3/_{16}$ inch) thick geonet having a transmissivity equivalent to 0.3 m (1 foot) of sand. The use of geonets can substantially reduce cover thickness, and they are easier to place than sand layers. All drainage materials must be separated from the overlying soil by adequate filters or filter fabrics to prevent the overlying soils from clogging the drainage material. Geotextiles are flexible, permeable, synthetic fabrics that make excellent filters. The properties of geosynthetic materials suitable for use in drainage layers are discussed in detail by Koerner and Daniel [34].

The drainage layer must slope to an exit drain at the toe of the slope that allows percolated water to be quickly removed. Care must be taken to provide adequate filtration around the drain to prevent plugging. Also, consideration should be given to designing protection for the toe drain to prevent freezing and to maintain its function. If drainage is critical, it may be necessary to bury the toe drain deep to prevent it from freezing.

Perhaps the most serious problem to be avoided with drainage layers is excessive long-term clogging of the drain materials. This is true for natural soil drains as well as geosynthetic drains. Excessive clogging can be prevented by incorporating a filter layer of soil or geotextile between the drainage layer and the overlying soil/protection layer. The prevention of biological clogging by plant roots is usually accomplished by using suitably thick surface protection layers, and by removing the water quickly so that plant roots cannot grow in the drain.

7.1.7 Filter Design

Filters are used to prevent excessive migration of soil particles while allowing relatively unimpeded flow of liquid or gas from the soil into a drainage layer or pipe. In landfill covers, filters are often placed above drainage or gas-collection layers to prevent them from clogging. Typically, they use one or more layers of carefully graded and placed granular materials, geotextiles, or a combination of these materials.

Experience has shown that the most common cause of drainage systems failure in landfill covers is the result of failing to provide an adequate filter. When drainage materials are placed adjacent to soil, an adequate filter should always be provided.

Filters must be sufficiently permeable to allow the free passage of liquids or gases, but they must also have small enough void space to prevent the movement of solids from the cover soil into the drain. Also, a filter must remain unclogged throughout its service life. Filters may be clogged by soil or by the growth of microorganisms. Rapid and complete drainage should provide adequate control of microorganism growth.

7.1.8 Gas Collection

There are two general approaches to gas control in landfills: passive and active systems. Passive systems use vent pipes, trenches, or membranes to convey the gases to the atmosphere. The pressure differential between the landfill and the atmosphere provides the driving force for the gas movement. Active gas protection systems employ extraction wells and vacuum pumps, fans, or blowers to draw gases from the landfill area. A description of various collection systems, along with their limitations, is provided in a report by the California Integrated Waste Management Board [13]. Disposal of the collected gas is discussed in Section 7.3.

Active gas removal systems are usually preferred under any of the following conditions [40]:

- The refuse is less than 20 years old and producing large volumes of gas.
- The refuse depth is greater than 10 m (approximately 33 feet).
- The property to be protected is less than 0.5 Km from the landfill boundary.

Sand and gravel are the most common materials used in gas collection layers. Any material used will need to be kept in a relatively dry state in order to maintain a high permeability to gas. A filter is usually needed to separate the sand or gravel from overlying materials, depending upon the materials involved. Designs that employ a geonet drain and geotextile fibers for the gas collection layer can be equivalent to sand and gravel layers. Further details on gas management systems may be found in publications by Koerner and Daniel [34], U.S. Environmental Protection Agency [14] and Landreth et al. [36].

The rate at which municipal waste generates gas increases for the first 5 or 6 years after placement in a landfill, and declines thereafter if no additional waste is added. Figure 11 shows a typical rate-of-gas production curve under conditions sufficiently wet to permit high decay rates. After placement of an adequate landfill cover, the waste will likely become too dry to maintain these rates of gas production. Results from typical field studies show that, after 15 years of landfill inactivity, between 60 and 85 percent of the potential methane production from landfill waste has already been produced [40].

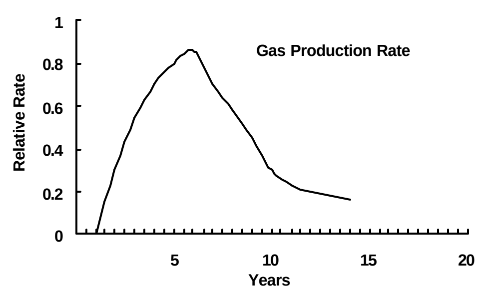

Figure 11. Typical Rate of Landfill Gas Production

Landfill gas emissions are site-specific functions of a number of factors and, therefore, difficult to predict accurately. Several equations have been proposed for estimating the rate of landfill gas production including the Scholl Canyon, Palos Verdes, Sheldon, GTLEACH-I, and a theoretical model based on biokinetics. The Scholl Canyon model is empirically derived and assumes that methane generation in the landfill follows first-order bacterial kinetics [65]. The model equation is as follows:

$$Q_{CH4} = L_o * R * (e^{-kc} - e^{-kt})$$

Where:

Q_{CH4} = methane generation rate at time t (m^3/yr)
L_o = potential methane generation capacity of the waste (m^3/Mg)
R = average annual acceptance rate of waste at the landfill (MG/yr)

k = methane generation rate constant (yr^{-1})
c = time since landfill stopped accepting waste (yr)
t = time since initial waste placement (yr)

The model must be calibrated to actual site data to be useful in predicting gas production rates. Unfortunately, all of the gas production models were created for predicting gas emission rates from active landfills and may not be very accurate for Air Force landfills that have been inactive for an extended period of time.

The waste in a typical Air Force landfill is likely to have remained wet and decayed rapidly during the time before final cover placement because the temporary covers that are commonly used allow part of the precipitation to pass through the cover and into the waste. Most Air Force landfills are more than 20 years old and are likely to produce only small amounts of landfill gas after cover placement because much—perhaps most—of the decay and resulting gas production occurred before remediation.

The placement of a cover will inherently reduce the rate of gas production because the intent of the cover is to stop water from moving into the waste. The production of gas will utilize some moisture to support the biological activity and the produced gas will carry off a portion of the moisture and gradually dry the waste. Therefore, alternative covers that do not include barrier layers may not require gas control, which could significantly reduce remediation costs.

Uncontrolled release of large amounts of landfill gas through the vegetative layers of the cover may prove to be harmful to the cover vegetation. At Glendale, California, a golf course was built on a landfill that had an insufficient cover and no gas control system. Fissures on the golf course and in the asphalt parking lot released methane. Small fires were reportedly ignited in the parking lot by sparks from passing cars. The golf course had to be closed because of excessive methane generation. The course was reopened after being covered with an additional 6 to 15 feet of soil. However, no gas control system was installed, so maintaining healthy vegetation continues to be a problem. The methane in the landfill gas displaces the oxygen in the soil. Since all plants require oxygen in the soil, some areas would not support grass and shrubs [49].

The production of large quantities of landfill gas under a barrier cover may result in mobilizing the contamination beyond the limits of the landfill. A buildup of gas pressure, blocked by the barrier layer, may move either laterally in the vadose zone or downward into the groundwater. The migrating gas may carry volatile contaminants, or it may provide a driving force for the movement of leachate. A gas collection layer must be incorporated into the design of the cover if significant quantities of gas are being produced by the landfill.

If gas control is not installed in a landfill with an impermeable GM barrier layer, even moderate gas production can create a large gas bubble that can lift the cover system [34]. Even if the GM is not physically lifted, positive gas pressure beneath the GM can lower the normal stress at the interface between the membrane and the underlying material, which reduces interface shear strength and could potentially contribute to a slope failure.

The landfill gas entering the cover's gas collection layer is transported by either a passive or active system out of the landfill. Passive transport relies on diffusion and the pressure difference between the landfill gas and the atmosphere to move the gas through the collection layer and piping to the surface for disposal.

Active gas collection systems use a vacuum blower or vacuum pump to produce a negative pressure in the collection system. Active collection may be required (and is strongly recommended) if there are nearby buildings to be protected from migrating landfill gas. Active collection can be designed to handle any quantity of gas produced.

Active collection from the gas collection layer of the landfill cover is a common approach. Gas extraction wells may also be used as a general collection system or to relieve gas pressure at hotspots in the landfill. McBean et al. [40] shows the construction of a gas extraction well, which is similar to the construction of a 4-inch PVC monitoring well extending into the waste.

Active collection usually requires a piping system to convey the gas from various points in the landfill to the vacuum system. The gas leaving the moist environment of the landfill will contain water vapor that may condense in the collection piping. In addition to water, the condensate may also contain concentrations of condensed hydrocarbon compounds and acids. It must either be returned to the landfill or be collected and treated similarly to landfill leachate.

7.1.9 Settlement and Subsidence

The harmful impact of settling upon the final cover is primarily due either to the resultant tearing or cracking of the cover components or to the change—or even reversal—in final cover system slopes. Such occurrences can affect the performance of the drainage and gas collection layers, as well as the overall water balance.

Othman et al. [48] list three causes of landfill cover settlement: settlement of foundation soils, settlement resulting from overall waste compressibility, and settlement caused by localized mechanisms. While settlement is possible, it is unlikely to be a major concern for military landfills that have been inactive for a long period of time.

7.1.10 Reuse of Landfill Areas

Land reuse is an important consideration in landfill cover selection. Former landfill sites find new life as parks, nature areas, and bicycle paths. However, some uses, such as golf courses, may produce significant liability for the landfill owner.

Nature areas and bicycle paths both allow covers that can maintain the surface soil in the driest state possible for the climate at the site. Therefore, these uses minimize the potential for water leakage through the cover and both are also aesthetically pleasing to the public. However, if the landfill produces significant amounts of landfill gas, the gas must be carefully controlled so that it does not pose a hazard to users.

Both bicycle and access paths for nature areas must be built to prevent excessive accumulations of water in the cover. Asphalt, gravel, and concrete walkways allow water movement through the surface and under the walkway by lateral infiltration from the edge. Because these walkway surfaces dramatically reduce evaporation from the surface, they will trap water in the cover and increase the amount of water moving downward through the cover. Therefore, pathway surfaces should be made as narrow as possible.

Golf courses are aesthetically pleasing and popular with the public. However, a golf course constructed on top of a landfill may have significant problems including constantly shifting surface grades, dead grass and fires on the surface resulting from landfill gas emissions, and damage to buildings from subsidence or by explosion of landfill gas [49].

Possibly the most serious long-term consequence resulting from constructing a golf course on top of a landfill results from irrigation of the fairways and greens. The frequent (often daily) irrigation may cause excessive amounts of water to move into the waste and increase the potential for groundwater contamination. Golf courses are irrigated frequently to maintain the desired turf quality. Deep percolation may result from two separate causes. First, excess irrigation water must be applied than used by the grass to leach salts out of the soil in order to maintain healthy grass. Second, a significant rainfall shortly after irrigation is almost certain to add substantially to the volume of deep percolation.

Deep percolation was reported from the irrigation of agricultural crops on a deep fertile soil in Nebraska [32]. The crops (corn and soybeans) were managed to use the least possible water to achieve acceptable crop yields and were irrigated only during the summer. During a five-year period, they measured between 127 and 193 mm/yr of deep percolation, depending on the crop, irrigation treatment, and weather. It is safe to assume that a well-managed golf course will produce much more than 127 mm/yr of deep percolation, which has the potential to enter the waste.

7.2 Design of Alternative Covers

The design of a conventional barrier-type landfill cover is described in detail in current texts [34]. While there are similarities between the design of conventional covers and alternative covers, there are significant differences as well. Most alternative cover designs rely on fine-grained soils to store infiltrating moisture. The ET cover and other vegetative covers depend upon both evaporation and transpiration by the vegetation to remove stored water from the cover soils.

The amount of cover soil required for an alternative cover depends upon the soil properties and upon the amount of infiltrating moisture that must be stored. In arid climates, the amount of moisture to be stored may be relatively small and the required soil depth small. In wetter climates, the amount of moisture to be stored may be large enough that the required depth of soil for water storage becomes large. In very wet climates, the depth of soil required to store the infiltrating moisture may be so large as to be uneconomical.

To gain regulatory acceptance for an alternative cover design, it will be necessary to demonstrate that the alternative design will meet the performance requirements and provide the same or better performance as the prescriptive barrier-type design. A demonstration, through modeling, that the alternative cover design will perform at least as well as the conventional design may be sufficient. The comparison should be based upon the worst-case conditions from as long a period as climate data is available (100 years in many parts of the country). This may be a straightforward exercise when comparing alternative design to a conventional compacted clay cover. However, estimating the actual performance of a composite barrier design that includes a GM is more difficult. None of the water balance models realistically accounts for imperfections in the GM.

The best field data available to show actual composite-barrier cover performance comes from Germany. Percolation through various barrier covers was measured over a period of eight years using well-monitored lysimeters at the University of Hamburg. The field data from these carefully constructed test plots suggests that a leakage rate of approximately 2 mm/yr is the lowest leakage rate that should be expected from the most carefully installed field installations

[42]. In typical field applications, imperfections in the GM installations will likely result in substantially higher leakage from the commercial composite barrier design than from was observed from this test plot.

Whatever performance standards are established, the demonstration of equal performance will require a significant effort up front to model and design an alternative cover. In locations suited to an alternative design, the extra work up front may be rewarded with a cover that performs as well or better than the prescriptive design at significantly less cost and with the possibility that less maintenance will be required over the life of the cover.

7.2.1 ET Cover Design

As stated above, the design of any landfill cover is dependent on factors that are specific to the site. In addition to the factors common to all landfill designs, ET cover design is dependent on local soil resources, potential ET, locally adapted native plants, and the interaction between climate, soil, plants and water balance. Each of these factors must be given special attention in ET cover design.

The technologies that affect the hydrologic design of ET covers encompass several scientific disciplines. As a consequence, a comprehensive computer model is needed. The model should effectively incorporate soil, plant, and climate variables and include their interactions and the resultant effect on hydrology and water balance. Because the expected life of the cover is decades, possibly centuries, the model should be capable of estimating long-term performance and the effect of extreme events. In addition to a complete water balance, the models long-term performance estimates should include plant biomass, need for fertilizer, wind and water erosion, unsaturated water movement, deep percolation, and possible loss of primary plant nutrients from the ecosystem. The EPIC model has been used to model ET cover water-balance estimates. The UNSAT-H model and others may also be applicable for this application.

A major concern for ET cover design and performance is determining the greatest amount of water that the ET cover soil must store. The critical event causing maximum soil water storage may result from a single-day storm or from a multiple-day storm. As an example, an ET cover was designed for a landfill located on the western edge of the Central Great Plains. The design was based upon EPIC modeling of soil water in storage for each day of a 100-year simulation period. Using a 100-year record of historical data as the design basis provides some assurance that the design will handle unusual climatic periods. The cover soil was 0.6 m (2 feet) thick and composed of loam soil. The plant cover included several native, cool-season grasses. Figure 12 shows the daily rainfall and the estimated daily soil water content during the wettest year of a 100-year period. This critical event period requires the largest daily soil water storage during the 100 years. In this example, the critical event was the result of several days of heavy rainfall followed by a

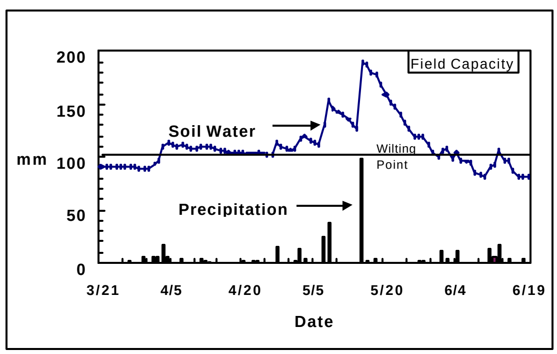

Figure. 12. Estimate of Critical Precipitation Event

large, single-day rainfall event. These calculations suggest that the ET cover design was adequate for the site.

The soil types selected for construction of an ET cover should have adequate water-holding capacity and must support robust plant growth. The ET cover functions by storing infiltration in the cover soil until ET can remove the excess moisture. Soils with significant amounts of clay and silt will provide good water-holding capacity. These soils, especially the clay fraction, will also hold adequate nutrients to support robust plant growth. Sandy soils have low water-holding and nutrient-holding capacity and are poorly suited for ET cover construction.

Excessive compaction of the cover soils will reduce or prevent growth of plant roots and will reduce the water-holding capacity of the soil. The installation contractor must be careful to maintain soil density between 1.1 and 1.5 Mg/m^3 (approximately 70-95 lb/ft^3). Wheeled vehicles should be kept off of the cover—both during and after construction—unless absolutely required. After placement, haul roads and other highly compacted areas must be loosened deep into the profile with a chisel, or ripping tooth, mounted on a tracked vehicle.

The soil of an ET cover allows the passage of landfill gas up through the profile. This enhanced porosity is due in part to the fact that the soil is not compacted to a high density. As a result, a gas collection layer may not be needed in an ET cover if the volume of gas produced is low, as might be expected at an Air Force landfill that has been inactive for many years.

7.3 Gas Disposal

The collection of landfill gases by a gas collection layer was discussed in Section 7.1.8. The following sections discuss issues related to the safe disposal of the collected gas. The details of designing gas disposal systems are presented in McBean et al. [40] and other recent texts.

The uncontrolled release of landfill gas can be a nuisance to neighbors, a contaminant to the environment, and a safety hazard to workers. Except in cases of very large landfills where gas recovery is practical, disposal is accomplished by one of two methods: controlled venting to the atmosphere or thermal destruction in a flare. Given the relatively small size of Air Force landfills, one or the other of these disposal options should be suitable.

7.3.1 Gas Venting

The simplest and lowest-cost method for disposing of landfill gas is controlled venting to the atmosphere. The most common type of vent consists of a pipe rising vertically from the gas collection layer or piping and passing through the cover to an appropriate height above the cover surface. Vent pipes are typically topped with a 180-degree bend fitting at the top to aim the vent opening toward the ground. This configuration prevents precipitation from entering the vent.

Venting does not destroy odors or toxic fumes in the landfill gas and therefore may not be an acceptable solution if public access to the site will be allowed after remediation is completed. Vents are generally applicable only for handling low gas emission rates.

Vent outlets should be designed to minimize the number of cover penetrations that could allow possible liquid infiltration through the cover. In passive gas collection systems, the vent outlets should be constructed through the barrier layer at the highest elevation of the gas vent layer to allow the maximum evacuation of gas. The vent outlet should also be designed and constructed sufficiently high above the landfill surface so that drifting snow will not cover and plug the vent.

Gas collection trenches may be installed around the periphery of the landfill to stop gas migration. An impermeable barrier of GM material is typically installed along the outside wall of the trench, and the trench is then filled with permeable material such as sand or fine gravel. An impermeable cover must be installed over the trench to keep it from filling with rainwater. Vent pipes are installed to release the gas at specific locations.

Open venting of landfill gas may be regulated and may require a permit from the state and/or local air quality board. In air quality non-attainment regions, this may not be permitted and treatment of the gas may be the only option. In other areas of the country, venting will be common practice and acceptable to the regulators.

Venting requires little O&M attention other than periodic inspection to ensure that none of the vents are plugged or damaged.

7.3.2 Landfill Gas Disposal

Burning landfill gas in a flare is a common form of landfill gas treatment at all but the largest landfill sites. Flaring is an open combustion process in which the oxygen required for combustion is provided either by ambient air or forced air. The landfill gas may be conveyed to the flare by the passive pressure in the collection system, but more often a blower or vacuum pump moves the gas in the collection system. A knock-out drum or tank is normally installed at the flare inlet to remove any remaining condensate, and the gas is then passed through a water seal before going to the flare. The water seal is a safety device to prevent possible flame flashbacks, which might occur when the gas flow rate is too low and the flame front moves down into the flare stack.

Two types of flares are in general use. The open-flame flare, or candle flare, represents the first generation of flares. The open-flame flare was mainly used for safe disposal of combustible gas when emission control was not a requirement. Similar flares are still used as emergency venting devices at petroleum refineries. The advantages of the open flame-flare are as follows:

- The design is simple and uncomplicated since combustion control is not possible.
- The device is easy to construct.
- Open-flame flares can be located at ground-level or elevated.
- It is the most cost-effective way of safely disposing of landfill gases.

However, the open-flame flare has the following disadvantages:

- The device does not have the flexibility to allow temperature control, air control, or sampling of combustion products because of its basic design
- It is not possible to design a system to accurately measure emissions.

Enclosed flares differ from open flares in that both the landfill gas and airflows are controlled. Landfill gas is pushed through the flame arrestor and burner tip by a blower. The flow of gas through the flare stack pulls air through dampers around the base to support combustion at the burner tip. The stack acts as a chimney, so its height and diameter are critical in developing sufficient draft and residence time for efficient operation. Enclosed flares provide a simple means of hiding the flame so they do not present a safety or public relations problem (neighbor-friendly). Enclosed flares are the only practical solution when emission monitoring is mandatory.

Both open and enclosed flares require a pilot-light assembly and a source of supplemental fuel (e.g., propane, natural gas). Flares require frequent operator attention to ensure that they are lighted and not malfunctioning. Periodic maintenance is required, along with replacement of worn or damaged parts. The cost of fuel and operator attention may become a significant continuing expense.

7.4 Leachate Collection and Treatment

As with gas collection and treatment, leachate collection and treatment is presented in detail in several recent texts. The following sections summarize some of the issues as they may pertain to Air Force landfills.

7.4.1 Bottom Liners

RCRA regulations presently require that new or currently operating landfills must have a bottom-liner systems under the waste to prevent the downward movement of leachate that might contaminate the groundwater. The implications for the design of a final cover system are that it will have to integrate and be compatible with the liner system design and that it may need to meet the Subtitle D requirement that the barrier layer in the cover must have a permeability equal to or less than that of the bottom liner. The Subtitle D permeability requirement essentially requires the use of a GM in the final cover system. Because less than 0.5 percent of Air Force landfills are estimated to have bottom liners [43], bottom liners will typically have little impact on decisions regarding covers for Air Force landfills.

7.4.2 Leachate Collection

Most Air Force landfills were constructed before the regulatory requirements for bottom liners and a leachate collection system. There is still the possibility, however, that leachate may be detected at the perimeter of the landfill. Collection and disposal of the leachate may be required as part of the landfill remediation.

If the leachate is migrating past the landfill perimeter over a relatively narrow area, or if the contamination is deep in the ground, extraction wells may be an appropriate and effective way of collecting the contamination. Leachate migration over a broad front and relatively shallow in the ground (less than approximately 30 feet deep) may require installation of a leachate collection gallery or trench with pumps installed to lift the contaminated water for treatment.

7.4.3 Leachate Treatment

Leachate has characteristics similar to concentrated industrial wastewater, as shown in Table 6. The treatment of leachate uses the same technologies as municipal and industrial wastewater treatment. Onsite leachate treatment is expensive and requires continuous O&M. Discharge of collected leachate to a POTW is a preferred option if a local POTW is willing to accept the leachate. The POTW may not be willing or able to accept the leachate if the leachate flow will significantly impact the hydraulic capacity of the POTW or if the leachate constituents may not be properly treated by the POTW resulting in the treatment facility violating its discharge permit. The details of leachate treatment, or pretreatment, are beyond the scope of this manual, and the reader is referred to recent texts on this subject [16][58][75].

7.5 Groundwater Control

Groundwater control and treatment, if required, may be handled as part of the landfill remediation or may be a separate remediation project. Typically, groundwater is extracted at the downgradient perimeter of the landfill to manage offsite migration of leachate by capturing the contaminated groundwater plume. The two types of groundwater collection systems used most often are extraction wells and subsurface drains.

Extraction wells are used more frequently than subsurface drains. Well diameter, flow rate, and spacing are determined based on the desired groundwater capture zone and the hydrological characteristics of the aquifer. Extraction wells and well fields are expensive and have proven to be ineffective in numerous cases. They should be selected only after careful evaluation of the problem.

Subsurface drains consist of underground, gravel-filled trenches that are generally equipped with tile or perforated pipe for greater hydraulic efficiency. The drains collect contaminated groundwater and transport it to a central area for treatment or proper disposal. Drains are typically used in geological units of low permeability.

Contaminated groundwater is usually treated in the same way as leachate. The chemical parameters that are typically elevated in samples of contaminated groundwater from landfill sites include BOD_5, COD, VOCs, TDS, chloride, nitrate and nitrite, ammonia, total phosphorus, sulfides, and metals. As with leachate, treatment of contaminated groundwater or pretreatment for discharge to a POTW may involve conventional treatment systems such as biological treatment for organic removal, metals precipitation, and air stripping or activated carbon adsorption for VOC removal.

Vertical barriers may be a viable technology for groundwater containment at a landfill site. Their use warrants some consideration since they may improve the overall effectiveness of the landfill containment system. The most common type of vertical barrier used at landfill sites is a soil-bentonite slurry wall. Extraction wells are often used with slurry walls to increase the effectiveness of the slurry wall by creating an inward groundwater gradient. In some cases, groundwater extraction wells alone may provide an adequate containment barrier to the migration contaminated groundwater.

An upgradient barrier may be used to reduce the amount of groundwater contacting a contaminated area, whereas a downgradient barrier may be used to restrict the migration of contaminated groundwater away from a contaminated area. These barriers acting alone are probably not suitable for most landfill sites because of their limited effects on movement of groundwater. It is difficult to completely intercept groundwater using just slurry walls.

The design and implementation of groundwater control technologies is beyond the scope of this manual. The reader is referred to the EPA Handbook *Groundwater, Volume I: Ground Water and Contamination* [77], the *Remediation Technologies Screening Matrix and Reference Guide* [67], and recent texts on these subjects.

7.6 Excavation/Consolidation

Removal of the waste or contaminated soils at landfill sites is generally limited to hotspots or to landfills with a low to moderate volume of waste (e.g., less than 100,000 cubic yards). Complete excavation of the landfill contents is often not considered practicable because of the large volume of waste typically found. However, this approach has been used at one or more Air Force bases where multiple small landfills were excavated and the waste deposited at one landfill site. Only the site receiving the waste requires long-term monitoring and maintenance, while the excavated sites can be cleaned and closed with no long-term monitoring required.

Excavation of waste or contaminated soils will require the use of standard construction equipment or specialized equipment adapted to minimize secondary migration and disturbance of the remaining deposit. Typically, mechanical equipment such as backhoes, bulldozers, and front-end loaders are used for the excavation. The use of scrapers and draglines usually makes it difficult to adequately control site dispersion. All excavations must be performed in accordance with the Occupational Safety and Health Association (OSHA).

In the event that full drums are encountered during the excavation, the hazards associated with the drums must be evaluated. Drum evaluation may be accomplished by staging, opening, and sampling and analysis, followed by transport and appropriate disposal. Ambient air should be monitored continuously during drum removal activities.

The following are some considerations for waste and soil excavation:

- Solid material above the water table can be excavated with very little secondary migration and good control of depth of cut. By using the proper excavation equipment and sediment control devices, the effect of surface runoff can be minimized.
- Good control of depth of excavation can be difficult underwater. In situations where excavation extends below the water table, dewatering is likely to be required. Consideration should be given to seasonal fluctuations in the water table. Significant shoring and dewatering costs may be eliminated by excavating at times when the water table is low. In some cases, excavation would require the construction of impermeable barriers and site dewatering.
- Enclosure of the air space in the excavation area may be necessary if VOC emissions are high.
- Potential exposure to workers and nearby communities during excavation must be considered. Enclosed cabs may be necessary to minimize operator exposure.
- Site accessibility to heavy equipment should be evaluated to determine whether track vehicles may be required.
- Waste disposal may require handling, stockpiling, and truck hauling of large volumes of material.
- The distance over which excavated material must be hauled should be evaluated to determine whether separate hauling equipment, such as dump trucks, are required.

8 Maintenance and Long-Term Monitoring

8.1 Maintenance

The monitoring of the surface of a landfill cover is straightforward. A dense grass cover will ensure no significant water or wind erosion, but the absence of cover on even small areas requires immediate investigation of the cause and requires corrective action. Even small rills demonstrate potentially bigger problems and require investigation and possible corrective action.

In arid regions where vegetation may not cover the whole surface, the formation of shrub-coppice dunes around shrubs may indicate either wind or water erosion and requires investigation. Where grass cover is moderate or better, there is little likelihood of significant wind erosion.

Where grass cover produces tall dry grass at the end of the growing season, mowing at a height of 4 to 6 inches after seed maturation may be appropriate to reduce the danger of wild fire. Mowing at intervals of 2 to 4 years may be required to prevent brush and tree invasion of the site. Erosion control maintenance includes routine vegetation management, subsidence repair, and run-on/run-off control. Sedimentation basins, waterways, drop structures and other structures, if used, should be inspected after every major rainstorm and repaired or cleaned if required.

Several authors have presented discussions of erosion control and vegetation establishment [12][34][40][48]. Modern textbooks discuss modern landfills that typically require covers over small mountains of waste with side slopes of 3:1 or 4:1 and surface areas of hundreds of acres. Under these conditions, revegetation and erosion control are both expensive and difficult. The designs for soil stabilization typically employ diversion terraces (under several names), chutes (lined with riprap), stilling basins, benches on side slopes, and engineering structures. These structures can be successful if they are rigorously maintained during every year of cover operation; otherwise, failure is likely. Maintenance of vegetation on the steep slopes may require frequent fertilization and irrigation to maintain healthy stands of even hardy native grasses.

Vent pipes in a passive gas venting system must be inspected frequently for damage that can be caused by mowing or other traffic. A damaged vent pipe can allow surface water to enter the gas-venting system and quickly bypass the cover. Damaged vent pipes must be repaired promptly.

Gas and leachate collection systems must be inspected at regular intervals to ensure that they are not plugged and are operating properly. Pumps and blowers, if needed, must be maintained in accordance with the manufacturer's recommendations.

In some cases, the maintenance issue can be folded into the land-use plan. If not, as is more frequently the case, constant vigilance is necessary and action must be taken as needed.

8.2 Long-Term Monitoring

A long-term monitoring plan will be required by the regulators as part of the remediation design and implementation. Groundwater monitoring is generally required. The parameters to measure will depend in part upon the groundwater contaminants that were found at the site during the FFS or earlier studies. Tables 9 and 10 list analytical parameters that might be appropriate. The required frequency of monitoring may be specified by regulation or may be negotiated. The AFCEE has published a document entitled *Long-Term Monitoring Optimization Guide* [63] that may be helpful after the long-term monitoring program is in place.

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Appendix A RCRA Subtitle C (Hazardous Wastes)

40 CFR 264.310 Closure and Post-Closure Care

(a) At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to:

- (1) Provide long-term minimization of migration of liquids through the closed landfill;
- (2) Function with minimum maintenance;
- (3) Promote drainage and minimize erosion or abrasion of the cover;
- (4) Accommodate settling and subsidence so that the cover's integrity is maintained; and
- (5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

(b) After final closure, the owner or operator must comply with all post-closure requirements contained in §§ 264.117 through 264.120, including maintenance and monitoring throughout the post-closure care period (specified in the permit under § 264.117). The owner or operator must:

- (1) Maintain the integrity and effectiveness of the final cover, including making repairs to the cover as necessary to correct the effects of settling, subsidence, erosion, or other events;
- (2) Continue to operate the leachate collection and removal system until leachate is no longer detected;
- (3) Maintain and monitor the leak detection system in accordance with §§ 264.301(c)(3)(iv) and (4) and 264.303(c), and comply with all other applicable leak detection system requirements of this part;
- (4) Maintain and monitor the ground-water monitoring system and comply with all other applicable requirements of subpart F of this part;
- (5) Prevent run-on and run-off from eroding or otherwise damaging the final cover; and
- (6) Protect and maintain surveyed benchmarks used in complying with § 264.309.

Appendix B RCRA Subtitle D (Municipal Solid Waste)

40 CFR 258, Subpart F—Closure and Post-Closure Care

§ 258.60 Closure criteria

(a) Owners or operators of all MSWLF [municipal solid waste landfill] units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:

(1) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than $1x10^{-5}$ cm/sec, whichever is less, and

(2) Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18-inches of earthen material, and

(3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth.

(b) The Director of an approved State may approve an alternative final cover design that includes:

(1) An infiltration layer that achieves an equivalent reduction in infiltration.

(2) An erosion layer that provides equivalent protection from wind and water erosion as the erosion layer specified in paragraph (a)(3) of this section.

Appendix C Texas Natural Resource Conservation Commission Proposed Chapter 350

Texas Risk Reduction Program
Rule Log No. 96106-350-WS

The Texas Natural Resource Conservation Commission (TNRCC) issued a new rule in the Texas Administrative Code (30 TAC) Chapter 350, effective 23 September 1999, concerning requirements pertaining to the assessment of property affected by chemicals of concern (COCs); the development of protective concentration levels for human and ecological receptors; the performance of response actions necessary to restore a property to active and productive use; required actions when substantial changes in circumstances occur at an affected property; the performance of post-response action care; the establishment and maintenance of financial assurance for post-response action care in certain circumstances; reporting requirements; and standardized deed recordation of restrictive covenant language.

Explanation of Rule

The Texas Risk Reduction Program (TRRP) rule establishes a uniform set of risk-based performance-oriented technical standards to guide response actions at affected properties regulated via the agency's Office of Waste Management program areas and other applicable program areas. Previously, several different rules governed corrective actions, closures, and post-closure care within the agency's waste management programs. The State Superfund program, the Industrial and Hazardous Waste program, and the Voluntary Cleanup Program (VCP) used the Risk Reduction Rules in 30 TAC Chapter 335, Subchapters A and S for risk-based corrective action. Any person who stores, processes or disposes of hazardous waste is also subject to the closure and post-closure care requirements in 30 TAC Chapter 335, Subchapters E and F. The Petroleum Storage Tank (PST) program uses 30 TAC Chapter 334, Subchapters D and G for risk-based corrective action. Corrective action and closure requirements for operating municipal solid waste landfills subject to federal Resource Conservation and Recovery Act (RCRA) Subtitle D requirements are found in 30 TAC Chapter 330. There are no specific corrective action requirements for other municipal landfills. Corrective action requirements for the Underground Injection Control (UIC) program are found in 30 TAC Chapter 331, Subchapter C. Spill response actions regulated under 30 TAC Chapter 327 that will take longer than six months to complete follow the Risk Reduction Rules or the PST rules, whichever is appropriate for a particular release. Currently, there are no rules for corrective action at compost facilities.

Chapter 350 is subdivided into Subchapters A through G. Subchapter A—General Information consists of §§350.1-350.5 and sets forth the general requirements of the TRRP rules. Subchapter B—Remedy Standards, §§350.31-350.37, establishes the requirements for two remedy standards (A and B). Subchapter C—Affected Property Assessment, §§350.51-350.55, establishes the necessary actions for property assessments. Subchapter D—Development of Protective Concentration Levels, §§350.71-350.79, establishes risk-based concentration levels. Subchapter E—Reporting Requirements §§350.91-350.96, describes the reporting and documentation required. Subchapter F—Institutional Controls §350.111, describes the requirements for filing deed notices and restrictions. Subchapter G—Establishing a Facility Operation Area §§350.131-350.135, describes procedures for handling multiple sources in within a chemical or petroleum manufacturing plant.

Subchapters B and D form the basis of the risk-based corrective action process. Subchapter D directs persons to evaluate exposure pathways and determine the concentration of the COC that is protective for human and ecological receptors at the point of exposure (POE) This concentration is referred to as risk-based exposure limits (RBELs). Separate RBELs are established for human and ecological receptors. For example, when a VOC is present in subsurface soils, vapors rise to the surface and are released into the air. The POE to air is where a receptor inhales the vapors. The RBEL is the concentration of the VOC in the air that is safe for the receptor to breathe assuming long-term, chronic exposure.

Persons then derive protective concentration levels (PCLs). PCLs are the concentration limits of COCs in the source media (e.g., soil and groundwater) that will achieve the RBELs in the exposure media. Continuing the example, the PCL is the concentration of the VOC in the subsurface soil that will, based upon modeling of cross-media transfer, achieve the RBEL for breathing the VOC at the POE in air. A tiered process is provided to establish both human health and ecological PCLs: Tier 1, 2 and 3. This tiered process for human health PCLs is patterned after the tiered process of the American Society of Testing and Materials *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites* ES-1739-95. Once PCLs are determined, the person must choose a remedy standard under Subchapter B. The person may choose one of two remedy standards, Remedy Standard A or Remedy Standard B. Remedy Standard A is a pollution cleanup approach and does not allow a person to use either physical or institutional controls, other than requiring a deed notice/restrictive covenant for commercial/industrial land use. Remedy Standard A requires that all media be removed or decontaminated to the applicable PCLs. Remedy Standard B allows exposure prevention approaches which rely on physical and/or institutional controls to protect human health and the environment. Persons may base remedy standards on residential or commercial/industrial land use as appropriate for the particular affected property. The following are excerpts to the sections describing the remedy standards.

§350.32. Remedy Standard A.

(a) To attain Remedy Standard A, the person shall:

(1) Remove any listed hazardous waste as defined in 40 CFR Part 261, Subpart D which is separable using simple mechanical removal processes;

(2) Remove and/or decontaminate any waste or environmental media which is characteristically hazardous due to ignitability, corrosivity, reactivity, or toxicity characteristic as defined in 40 CFR Part 261, Subpart C;

(3) Remove and/or decontaminate the soil and groundwater protective concentration level exceedance (PCLE) zones (monitored natural attenuation can be used when appropriate considering the hydrogeologic characteristics of the affected property and chemical-specific data), other environmental media, and non-hazardous waste to the critical residential or commercial/industrial PCLs or source medium PCLs, as applicable; and

(4) Demonstrate that the affected property is protective for ecological receptors.

(b) Response actions under Remedy Standard A must result in permanent risk reduction at an affected property. The person shall not use physical controls under Remedy Standard A. The person shall remediate the affected property such that the concentration of COCs in surface soil, subsurface soil, groundwater, and other environmental media do not exceed the applicable critical PCLs.

(c) The person shall determine the PCLs for Remedy Standard A using exposure pathways where the human or ecological receptor comes into contact with the COCs directly within, above, or below a source medium. Lateral transport considerations which place the POE at a location outside of the source area cannot be used to determine PCLs for Standard A response actions with the exception, when necessary, the person shall perform lateral transport calculations to determine whether PCLs calculated based upon on-site commercial/industrial workers are protective of off-site residents.

(d) Remedy Standard A is a self-implementing standard unless the person desires to modify exposure factors under §350.74 of this title (relating to Development of Risk-Based Exposure Limits) which requires prior executive director approval, or unless the person chooses not to self-implement. If the person chooses not to self-implement, then the person shall submit a Response Action Plan (RAP) for review and approval by the executive director.

(e) The person cannot use a demonstration of technical impracticability when responding to soil and/or groundwater PCLE zones, or other affected environmental media under Remedy Standard A.

(f) The person shall prevent COCs at concentrations above the critical groundwater PCLs from migrating beyond the existing boundary of the groundwater PCLE zone.

(g) There are no post-response action care or financial assurance requirements for Remedy Standard A response actions, provided the person adequately documents attainment of the response objectives provided in subsection (a) of this section. When considered warranted, the executive director may require the person to monitor environmental media to verify that the models used to determine PCLs established under Tiers 2 or 3 as provided in §350.75 of this title (relating to Tiered Human Health Protective Concentration Level Evaluation) yield protective PCLs.

§350.33. Remedy Standard B.

(a) To attain Remedy Standard B, the person shall:

(1) Remove, decontaminate, and/or control the surface soil, subsurface soil, and groundwater human health PCLE zones, other environmental media, and hazardous and non-hazardous waste in accordance with the provisions of this section such that humans will not be exposed to concentrations of COCs in the exposure media in excess of the residential or commercial/industrial critical human health PCLs, as applicable, at the prescribed, or any approved alternate POEs established for environmental media in accordance with §350.37 of this title (relating to Human Health Points of Exposure);

(2) Ensure that leachate from the surface and subsurface soil PCLE zones does not increase the concentration of COCs in class 2 groundwater above the measured concentration at the time of RAP submittal in circumstances when an alternate POE class 2 groundwater is authorized in response to subsection (f)(4) of this section; and

(3) Use either subparagraph A or B to respond to an affected property when either the initial concentrations of COCs within environmental media exceed only the ecological PCLs or when there will be residual concentrations of COCs above the ecological PCLs following completion of a human health response action.

(A) The person shall remove, decontaminate, and/or control the environmental media, and hazardous and non-hazardous waste in accordance with the provisions of this section such that ecological receptors will not be exposed to concentrations of COCs in the exposure medium in excess of the ecological PCLs at the POEs determined in accordance with §350.77 of this title (relating to Ecological Risk Assessment and Development of Ecological Protective concentration Levels).

(B) When it is determined appropriate by the executive director, the person may use the results of a Tier 2 or 3 ecological risk assessment performed in accordance with §350.77 of this title (relating to Ecological Risk Assessment and Development of Ecological Protective concentration Levels) and other appropriate information or data to conduct an ecological services analysis of the affected property. However, an ecological services analysis must be conducted whenever concentrations of COCs which exceed ecological PCLs are proposed to be left in place with the potential for continuing exposure. The ecological services analysis must, at a minimum, include an evaluation of the effects of reasonable and feasible remediation alternatives, including complete removal/decontamination to PCLs and a control measure to prevent ecological exposure to COCs in excess of ecological PCLs, with respect to present and predicted losses of ecological services; and clear justification for leaving COCs in place above ecological PCLs. Furthermore, the person shall also ensure, where appropriate, that the ecological services analysis includes a plan to provide compensatory ecological restoration which may also be combined with some type of active response action (e.g., hotspot removal) or passive response action (e.g., natural attenuation) for the affected property. The ecological services produced by the restoration activity must exceed the future ecological service decrease potentially associated with the continued exposure to COCs and/or any selected response action at the affected property. The person must conduct the compensatory ecological restoration and other activities associated with the ecological services analysis with the approval of and in cooperation with the Natural Resource Trustees. The executive director may develop guidance which further describes the ecological services analysis process.

(b) As defined further by the surface and subsurface soil response objectives in subsection (e) of this section and the groundwater response objective in subsection (f) of the section, the person performing a response action to attain Remedy Standard B may use removal and/or decontamination, removal and/or decontamination with controls, or controls only, with the exception of response actions for Class 1 groundwater PCLE zones which must be removed and/or decontaminated to the critical groundwater PCL for each COC.

(1) The person may use both physical and institutional controls.

(2) For all actions to attain Remedy Standard B, The person shall demonstrate that the response actions which they propose to use will attain the requirements of subsection (a) of this section within a reasonable time frame given the particular circumstances of an affected property. Remedial alternatives, including the use of monitored natural

attenuation as a decontamination or control remedy, must be appropriate considering the hydrogeologic characteristics of the affected property, COC characteristics, and the potential for unprotective exposure conditions to continue or result during the remedial period.

(c) PCLs for Remedy Standard B are determined through consideration of on-site and off-site POEs, or alternate POEs.

(d) Remedy Standard B is not a self-implementing standard. The person must receive the executive director's written approval of a RAP and an Affected Property Assessment Report (APAR), either submitted at the same time as the RAP or previously, before commencing response actions to attain the standard, but this does not preclude the person from taking interim measures.

(e) The following are the Remedy Standard B surface and subsurface soil response objectives and associated requirements for response actions performed in accordance with subsections (a)(1) – (2), and (a)(3)(A) of this section to address human health and/or ecological risks at the affected property. A person may choose to attain the surface and subsurface soil response objectives for an affected property either by conducting a response action which makes use of removal and/or decontamination or by conducting a response action which makes use of removal and/or decontamination with controls or controls only.

(1) When all surface and subsurface soil response objectives specified in subsection (a) of this section are met through removal and/or decontamination, the person shall fulfill any post-response action care obligations described in the approved RAP, but shall not be required to provide financial assurance for the soils.

(2) When a person chooses to attain the surface and subsurface soil response objectives specified in subsection (a) of this section for an affected property by conducting a response action which uses removal and/or decontamination with controls or controls only, then the person must also comply with the requirements of this paragraph.

(A) The person shall demonstrate that any physical control or combination of measures proposed to be used (e.g., waste control unit, cap, slurry wall, treatment that does not attain decontamination, or a landfill) will reliably contain COCs within and/or derived from the surface and subsurface soil PCLE zone materials over time.

(B) The person shall fulfill the post-response action care obligations described in the approved RAP.

(C) The person shall provide financial assurance in accordance with subsections (l) and (m) of this section.

(f) [Subsection 350.33 (f) describes the Remedy Standard B groundwater response objectives and associated requirements for response actions.]

(g-j) [Subsections 350.33 (g) through 350.33 (j) describe the type, method and extent of post-response action care, and related topics.]

(k) [Subsection 350.33 (k) describes record keeping and reporting requirements for Remedy Standard B.]

(l-n) [Subsections 350.33 (l) through 350.33 (n) describe financial assurance requirements for Remedy Standard B.]

Appendix D California Regulations

§21090. SWRCB—Closure and Post-Closure Maintenance Requirements for Solid Waste Landfills (C15: §2581 // T14: §17777, §17779)
[Note: For SWRCB's final cover performance standard, see §20950(a)(2)(A); for related CIWMB requirements, see §21790 et seq.]

(a) **Final Cover Requirements—**Final cover slopes shall not be steeper than a horizontal to vertical ratio of one and three quarters to one, and shall have a minimum of one fifteen-foot wide bench for every fifty feet of vertical height. Designs having any slopes steeper than a horizontal to vertical ratio of three to one, or having a geosynthetic component [under ¶(a)(2)], shall have these aspects of their design specifically supported in the slope stability report required under §21750(f)(5). The RWQCB can require flatter slopes or more benches where necessary to ensure preservation of the integrity of the final cover under static and dynamic conditions. The cost estimate, under §21769, for the final cover shall include a description of the type and estimated volume (or amount, as appropriate) of material needed for each component of the final cover based upon the assumption that all materials will need to be purchased; if on-site materials are to be used, the submittal shall include test results confirming the availability of such on-site materials and their suitability for such use. The RWQCB [Regional Water Quality Control Board] can allow any alternative final cover design that it finds will continue to isolate the waste in the Unit from precipitation and irrigation waters at least as well as would a final cover built in accordance with applicable prescriptive standards under ¶(a)(1-3).

(1) Foundation Layer—Closed landfills shall be provided with not less than two feet of appropriate materials as a foundation layer for the final cover. These materials may be soil, contaminated soil, incinerator ash, or other waste materials, provided that such materials have appropriate engineering properties to be used for a foundation layer. The foundation layer shall be compacted to the maximum density obtainable at optimum moisture content using methods that are in accordance with accepted civil engineering practice. A lesser thickness may be allowed for Units if the RWQCB finds that differential settlement of waste, and ultimate land use will not affect the structural integrity of the final cover.

(2) Low-Hydraulic-Conductivity Layer—In order to protect water quality by minimizing the generation of leachate and landfill gas, closed landfills shall be provided with a low-hydraulic-conductivity (or low through-flow rate) layer consisting of not less than one foot of soil containing no waste or leachate, that is placed on top of the foundation layer and compacted to attain an hydraulic conductivity of either $1x10^{-6}$ cm/sec (i.e., 1 ft/yr.) or less, or equal to the hydraulic conductivity of any bottom liner system or underlying natural geologic materials, whichever is less permeable, or another design which provides a correspondingly low through-flow rate throughout the post-closure maintenance period. Hydraulic conductivity determinations for cover materials shall be as specified in Article 4, Subchapter 2, Chapter 3 of this subdivision [§20310 et seq.], but using water as the permeant, and shall be appended to the closure and post-closure maintenance

report. For landfills or portions thereof in which the final cover is installed after July 18, 1997, as part of the final closure plan for the Unit, the discharger shall provide a plan, as necessary [see ¶(a)(4)], for protecting the low-hydraulic-conductivity layer from foreseeable sources of damage that could impair its ability to prevent the through flow of water (e.g., desiccation, burrowing rodents, or heavy equipment damage).

§20080. SWRCB—General Requirements. (C15: §2510)

20080(4)(b) Engineered Alternatives Allowed—Unless otherwise specified, alternatives to construction or prescriptive standards contained in the SWRCB-promulgated regulations of this subdivision may be considered. Alternatives shall only be approved where the discharger demonstrates that:

(1) the construction or prescriptive standard is not feasible as provided in ¶(c); and

(2) there is a specific engineered alternative that:

(A) is consistent with the performance goal addressed by the particular construction or prescriptive standard; and

(B) affords equivalent protection against water quality impairment.

(c) Demonstration [for ¶(b)]—To establish that compliance with prescriptive standards in this subdivision is not feasible for the purposes of ¶(b), the discharger shall demonstrate that compliance with a prescriptive standard either:

(1) is unreasonably and unnecessarily burdensome and will cost substantially more than alternatives which meet the criteria in ¶(b); or

(2) is impractical and will not promote attainment of applicable performance standards.

The RWQCB shall consider all relevant technical and economic factors including, but not limited to, present and projected costs of compliance, potential costs for remedial action in the event that waste or leachate is released to the environment, and the extent to which ground water resources could be affected.

Appendix E Web Sites with Important Innovative Technology Resources

www.epa.gov/swerrims/

The Office of the Assistant Administrator of EPA for Solid Waste and Emergency Response provides Agency-wide policy, guidance and direction for the Agency's solid waste and emergency response programs, they:

- Develop guidelines and standards for the land disposal of hazardous wastes and for underground storage tanks.
- Furnish technical assistance in the development, management and operation of solid waste activities and analyze the recovery of useful energy from solid waste.
- Are developing and implementing a program to respond to abandoned and active hazardous waste sites and accidental release (including some oil spills) as well as the encouragement of innovative technologies for contaminated soil and groundwater.

www.epa.gov/epaoswer/osw/index.htm

EPA's Office of Solid Waste home page. The link under "Municipal Solid Waste" to "Landfills" leads to general information and links to EPA publications on landfill remediation technologies and regulations.

www.epa.gov/swerffrr/

This Web site is for the Federal Facilities Restoration & Reuse Office (FFRRO). FFRRO's Mission is to facilitate faster, more effective, and less costly cleanup and reuse of federal facilities. By focusing on teamwork, innovation, and public involvement, FFRRO and its Regional counterparts improve environmental cleanup, while protecting and strengthening the conditions of human health, the environment, and local economies.

www.clu-in.org

The Hazardous Waste Clean-Up Information (CLU-IN) Web Site provides information about innovative treatment technology to the hazardous waste remediation community. It describes programs, organizations, publications, and other tools for federal and state personnel, consulting engineers, technology developers and vendors, remediation contractors, researchers, community groups, and individual citizens. The site was developed by the U.S. EPA, but it is intended as a forum for all waste remediation stakeholders.

www.rtdf.org

The purpose of the RTDF is to identify what government and industry can do together to develop and improve the environmental technologies needed to address their mutual cleanup problems in the safest, most cost-effective manner. The RTDF fosters public and private sector partnerships to undertake the research, development, demonstration, and evaluation efforts needed to achieve common cleanup goals.

www.afcee.brooks.af.mil/er/erhome.asp

The AFCEE Environmental Restoration page has links to a list of products which include the AFCEE analytical protocols, the model QAPP, and the field sampling plan document. Other useful documents are also available from this site.

www.wes.army.mil/el/homepage.html

The HELP model and its documentation are available free for downloading from the U.S. Army Corps of Engineers (USACE)Waterways Experimental Station.

etd.pnl.gov:2080/~mj_fayer/unsath.htm

This site at Pacific Northwest National Laboratory is the source for information about the DOS version of the UNSAT-H model, and the Internet address for downloading the program.

www.ncdc.noaa.gov/ol/climate/climatedata.html#DAILY

This site is the National Climatic Data Center of NOAA is a free source for climatic data. Some of this data may have to be manipulated to put it into a format usable for water balance modeling.

www.earthinfo.com/earthinfo

This is a commercial site for climatic data. There is a cost for the data, but it is relatively inexpensive, and the data is available on CD-ROM in a readily usable format.

www.statab.iastate.edu/soils/nsdaf/

This is the National Soil Data Access Facility of the USDA. This is a source of soil survey maps and attributes and soil survey reference data

www.usace.army.mil/inet/usace-docs/

This site is the repository for publications by the USACE. Many of the Corps' documents are available in .pdf format for download. Included at this site are Technical Manuals, Engineering Manuals, and Guide Specifications for Construction (GSC).

Appendix F Topical Bibliography

This bibliography contains references that are useful to the study of modern and innovative landfill covers. References are classified by subject although many of them cover more than one subject. The classification was primarily based on words contained in the title. Textbooks, proceedings, design, and construction titles are likely to contain material pertinent to several subjects. The references are divided into the following subjects:

1. Clay Barriers
2. Closure
3. Computer Models
4. Design and Construction
5. General
6. Geosynthetic Components
7. Hydrology
8. Innovative Covers
9. Leachate, Gas and Waste Decomposition
10. Leakage
11. Military
12. Regulations
13. Soil Erosion and Seismic Design
14. Textbooks, Proceedings, Seminars
15. Vegetation

14. Clay Barriers

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Appendix G Glossary of Terms

AERATION, SOIL: The process by which air in the soil is replenished by air from the atmosphere. In a well-aerated soil, the air in the soil is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen. The rate of aeration depends largely on the volume, size and continuity of pores in the soil.

AMENDMENT: Any material—such as lime, gypsum, sawdust, or synthetic conditioners—that is worked into the soil to make it more productive. The term is used most commonly for added materials other than fertilizer.

ANIMAL INTRUSION LAYER: Layer in a landfill cover intended to prevent burrowing animals from penetrating the waste or damaging the cover. For example: layer of cobbles or gravel and cobbles.

ATTERBERG LIMITS: A collective designation of seven so-called limits of consistency of fine-grained soils, suggested by Albert Atterberg, but with current usage usually referring only to the liquid limit, the plastic limit, and the plasticity number.

BARRIER-TYPE COVER: A cover that is designed to prevent water infiltration into the waste by repelling it using very low permeability barriers such as a compacted clay liner, geosynthetic clay liner, flexible membrane or some combination.

BENTONITE: A relatively soft rock formed by chemical alteration of glassy, high silica content volcanic ash. The principal mineral constituent is clay size smectite. It swells extensively in water, has a high specific surface area and it is used in sealing applications in landfills and for sealing wells because it has low hydraulic conductivity when hydrated..

BIODEGRADABLE: Capable of being decomposed by natural biological processes.

BIOINTRUSION LAYER: Layer in a landfill cover used to prevent plant roots and/or burrowing animals from penetrating the waste or otherwise damaging the cover. For example, a layer of cobble or grave.

BULK DENSITY, SOIL: The mass of soil per unit bulk volume, often expressed as g/cm^3.

CAPILLARY ACTION (**CAPILLARITY**): The rise or movement of water in a porous media due to capillary forces.

CAPILLARY BARRIER: Landfill cover designed to prevent water infiltration by using the capillary force at the interface between layers of fine over coarse grained materials to increase the water-holding capacity of the fine-grained soil.

CAPILLARY FORCE: See ***CAPILLARY PRESSURE***

CAPILLARY PRESSURE: The difference in pressure across the interface between two immiscible fluid phases (normally air and water) jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface.

CATION EXCHANGE CAPACITY: The sum of exchangeable bases plus total soil acidity at a specific pH value, usually 7.0 or 8.0. Usually expressed in meq (milliequivalents) per 100 grams of soil.

CELL: Portion of waste in a landfill that is isolated horizontally and vertically from other portions of waste in the landfill by means of a soil barrier.

CHUTE: An open channel for conveying water at high velocity to a lower level.

CLAY: A soil separate consisting of particles <0.002 mm in equivalent diameter..

COBBLE: Rounded or partially rounded stone or mineral fragments between 75 and 250 mm.

COEFFICIENT OF PERMEABILITY: The rate of discharge of water under laminar-flow conditions and at a standard temperature (usually 20°C) through a unit cross-sectional area of a porous medium under a unit hydraulic gradient. Frequently simply termed "permeability" in soil-mechanics usage. See ***PERMEABILITY***.

COMPACTED CLAY LAYER (CCL): Layer in a landfill cover or bottom liner that is composed of clay compacted to prevent passage of water.

COVER MATERIAL: A soil or other suitable material that is used to cover the liner or wastes in a disposal site.

COVER, FINAL: The cover material that is applied at the end of the useful life of a disposal site and represents the permanently exposed final surface of the fill.

DIFFERENTIAL SETTLEMENT: Uneven settlement of landfill cover due to uneven settlement of underlying wastes as decomposition progresses.

DIKE: A barrier to the flow of surface waters formed by a raised embankment.

DUCTILE: Capable of being deformed without failure.

EFFECTIVE DIAMETER: Grain size diameter at which 10% by weight of soil particles are finer and 90% are coarser.

EPIC: Environmental Policy Integrated Climate model. Numerical model that simulates physical processes involved in water movement. Developed by the United States Department of Agriculture.

EROSION: The wearing away of a land surface by moving water, wind, ice, or other geological agents.

ET COVER: The ET (evapotranspiration) landfill cover consists of a layer of soil covered by native grasses. The soil contains no barrier or impermeable layers and uses two natural processes to control infiltration. The uncompacted soil provides a water reservoir. The natural mechanisms of ET empties the soil water reservoir.

EVAPOTRANSPIRATION (ET): The combined processes by which water is transferred from the earth surface to the atmosphere. The evaporation of water from the soil plus transpiration from plants.

FERTILITY (SOIL): The relative ability of a soil to supply the nutrients essential to plant growth.

FIELD CAPACITY: The content of water remaining in a soil 2 or 3 days after having been wetted with water and free drainage is negligible. For practical purposes, the water content when soil matrix potential is –1/3 atmospheres.

FILTER: A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles by water flowing through the soil pores.

FLEXIBLE MEMBRANE COVER: Landfill cover which uses flexible membrane material as the primary barrier to water infiltration.

FLEXIBLE MEMBRANE LINER: See ***GEOMEMBRANE***

FOUNDATION: Lowermost layer in a landfill cover. Placed to produce a firm foundation and the proper gradient for overlying layers. Normally compacted to some extent.

GEOCOMPOSITE: Composite of geosynthetic materials or geosynthetic material combined with another material such as clay. For example, a high strength geosynthetic may be combined with a high permeability geosynthetic. See also ***GEOSYNTHETIC CLAY LINER***.

GEOMEMBRANE: A flexible, very low permeability, thin sheet of rubber or plastic material used primarily for linings and covers of liquid or solid storage impoundments, thus serving as a moisture or fluid barrier.

GEONET: Geosynthetic material formed by continuous extrusion of parallel sets of polymeric ribs at acute angles. When material is put under tension, the ribs open to form a highly permeable flow path. Used for drainage in place of (or to enhance) more traditional drainage layers composed of coarse-grained sand or gravel. (also known as geospacers)

GEOSYNTHETIC CLAY LINER: Geocomposite composed of thin layers of bentonite clay sandwiched between two geotextiles or bonded to a geomembrane. Used as water flow barrier.

GEOSYNTHETIC: Any of several synthetic materials used in geotechnical applications including blocking moisture, enhancing drainage and enhancing slope stability. See also ***GEOMEMBRANE, GEONET, GEOTEXTILE.***

GEOTEXTILE: A flexible, porous (to water flow) synthetic fabric used in soil construction for applications such as separation, reinforcement, filtration, or drainage.

GRADATION (**GRAIN-SIZE DISTRIBUTION**) (**PARTICLE-SIZE DISTRIBUTION**) (**SOIL TEXTURE**): Proportion of material of each grain size present in a given soil.

GRADE: 1. The slope of a road, channel, or natural ground. 2. The finished surface of a canal bed, roadbed, top of embankment, or bottom of excavation; any surface prepared for the support of construction like paving or laying a conduit. 3. To finish the surface of a canal bed, roadbed, top of embankment, or bottom of excavation.

GRADIENT: The degree of slope or a rate of change of a parameter measured over distance.

GRAVEL: Unconsolidated granular mineral material of pebble sizes. Rounded or semi-rounded particles of rock ranging from 2 to 75 mm in diameter.

GROUND COVER: Grasses or other plants grown to keep soil from being blown or washed away.

GROWING SEASON: The period and/or number of days between the last freeze in the spring and the first frost in the fall for the freeze threshold temperature of the crop or other designated temperature threshold.

GULLY: A channel resulting from soil erosion and caused by the concentrated but intermittent flow of water usually during and immediately following heavy rains. A gully is sufficiently deep that it would not be obliterated by normal tillage operations, whereas a rill is of lesser depth and would be smoothed by ordinary farm tillage.

HAZARDOUS WASTE: A solid waste or combination of solid wastes, which because of its quantity, concentration or physical, chemical, or infectious characteristics may:

- Cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or Pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed (Public Law 94-580, 1976).

HEAD: A measure of the energy that water possesses by virtue of its elevation, pressure, or velocity. The components Elevation Head, Pressure Head, and Velocity Head combine to make Total Head. All heads are expressed in linear units, e.g. feet. At all points in a body of water at rest, the total head (equals static head) is the same, pressure heads exactly compensating elevation heads, and velocity heads being zero. Water flows spontaneously from paints of higher to points of lower total head.

HELP: Hydrologic Evaluation of Landfill Performance. Numerical model used to predict percolation of water through landfill cover and leachate generation. Developed by US Army Corps of Engineers for the US Environmental Protection Agency.

HORIZON (**SOIL HORIZON**): One of the layers of the soil profile, distinguished principally by its texture, color, structure, and chemical content.

- **A HORIZON**: The uppermost layer of a soil profile. Usually contains remnants of organic life.
- **B HORIZON**: The layer of a soil profile in which material leached from the overlying A horizon is accumulated.
- **C HORIZON**: Parent material from which the overlying soil profile has been developed.

HYDRATED: Combined with water.

HYDRAULIC CONDUCTIVITY: Term used in groundwater hydrology and soil science. Equivalent to Coefficient of Permeability.

IMPERMEABLE: Not permitting passage of a fluid or a gas through its substance.

IN SITU: In its natural or original position.

INDICATOR PLANTS: Plants characteristic of specific soil or site conditions.

INDUSTRIAL WASTE: Waste from industrial processes, as distinct from municipal solid waste.

INFILTRATION RATE (**INFILTRATION CAPACITY**): A soil characteristic determining the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. It has the dimensions of velocity.

INFILTRATION: The downward entry of water into the soil.

INNOVATIVE COVER: A cover that meets regulatory requirements for results (for instance: limits water infiltration, isolates wastes…) while not using specific design elements mandated by those regulations or customarily used

LEACHATE: Liquid that has percolated through or drained from a material (such as waste in a landfill) and contains soluble, partially soluble, or miscible components removed from such material.

LEACHING: The removal from soil or waste of the more soluble materials, in solution, by percolating waters.

LIFT: A single layer of compacted soil. Lift thickness depends on soil and degree of compaction needed (also termed "course").

LINER: A layer of emplaced material beneath a surface impoundment or landfill which is intended to restrict the escape of waste or its constituents from the impoundment or landfill. May include reworked or compacted soil and clay, asphaltic and concrete materials, spray-on membranes, polymeric membranes, chemisorptive substances, or any substance that serves the above stated purpose.

LOAM: Soil material that contains 7 to 27 percent clay, 28 to 50 percent silt and <52 percent sand.

LYSIMETER: A device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis.

MATRIC POTENTIAL: The amount of work that must be done to permanently move (without change in temperature) an infinitesimal quantity of water from a specified source to a specified destination. Also known as soil water potential.

MIL: Unit of length, equal to .001 inch or .0254 mm.

MIXED WASTE: Waste composed of any combination of the following: municipal, industrial, hazardous or radioactive.

MOISTURE CONTENT: See ***WATER CONTENT***.

MONOFILL COVER (MONOCOVER): Relatively simple single soil layer landfill cover. Soil may or may not be compacted. Used in arid or semi-arid climate.

MULCH: A natural or artificial layer of plant residue or other materials, such as sand or paper, on the soil surface.

MUNICIPAL SOLID WASTE: Solid waste collected from residential and commercial sources in bins and other large containers.

NATIVE SPECIES: A species that is part of an area's original fauna or flora.

NUTRIENTS: 1. Elements, or compounds, essential as raw materials for organism growth and development, such as carbon, oxygen, nitrogen, phosphorus, etc. 2. The dissolved solids and gases of the water of an area.

PARENT MATERIAL: The unconsolidated and more or less chemically weathered material (normally rock) from which soil is developed.

PARTICLE SIZE: The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

PEBBLE: Rounded or semi-rounded rock or mineral fragment between 2 and 75 mm in diameter. Fragment size found in gravel.

PERCHED WATER TABLE: A water table usually of limited area maintained above the normal free water elevation by the presence of an intervening relatively impervious confining stratum.

PERCOLATION: Downward movement of water through soil. Especially, the downward flow of water in saturated or near-saturated soil at hydraulic gradients of the order of 10 or less.

PERENNIAL PLANT: A plant that normally lives three or more years.

PERMEABILITY: Capability of a material to transmit fluid through its substance.

POLYVINYL CHLORIDE (PVC): A synthetic thermoplastic polymer prepared from vinyl chloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of sheeting.

PORE WATER PRESSURE: See ***STRESS***

PORE: A small to minute opening or passageway in a rock or soil; an interstice.

POROSITY: The ratio, usually expressed as a percentage, of the volume of voids of a given soil mass to the bulk (total) volume of the soil mass.

PREFERENTIAL FLOW: The process whereby free water and its constituents move by preferred pathways through a porous medium (such as along the interface between soil and plant roots, cracks, or other channels).

PRINCIPAL THREAT WASTES: waste materials that are highly toxic and/or highly mobile, generally cannot be reliably contained, and could present substantial threat to human health or the environment if released (e.g., liquids in drums or tanks; free product non-aqueous phase liquids [NAPLs] in contact with groundwater; surface soil with dust-associated COCs). [74]

PROCTOR TEST: A test method to determine the relationship between water content and dry unit weight of soils (compaction curve) compacted using a standardized effort (12,400 ft-lb_f/ft^3). The commonly accepted standard for the method is presented ASTM Standard D698.

REVEGETATION: Plants or growth that replaces original ground cover following land disturbance.

RILL: Small intermittent water channel, usually only several centimeters deep. Normally formed by erosion of recently cultivated soils.

RIPRAP: Broken rock, cobbles, or boulders placed on earth surfaces, such as the face of a dam or the bank of a stream, for protection against the action of water waves. Also applied to brush or pole mattresses, or brush and stone, or other similar materials used for soil erosion control.

ROOT ZONE: The part of the soil that is penetrated or can be penetrated by plant roots.

RUNOFF: That portion of precipitation or irrigation water that drains from an area as surface flow.

SAND: Unconsolidated granular mineral material ranging from 0.25 to 2 mm in diameter.

SATURATION: The point at which all voids in a material are filled with water.

SEED: The fertilized and ripened ovule of a seed plant that is capable, under suitable conditions, of independently developing into a plant similar to the one that produced it.

SEEPAGE: Slow movement of water through soil.

SEMI-ARID: Marked by light annual rainfall and capable of sustaining only short grasses and shrubs.

SHEAR STRENGTH: The maximum resistance of a material to shearing stresses.

SHRUB: A woody perennial plant differing from a tree by its low stature and by generally producing several basal shoots instead of a single bole.

SILT (**SILT SOIL**): Soil material that contains 80% or more silt and < 12% clay.

SLOPE: Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees. In engineering, usually expressed as a ratio of horizontal to vertical change. See also ***GRADE***.

SOD: A closely knit groundcover growth, primarily of grasses.

SOIL PROFILE (**PROFILE**): Vertical section of a soil, showing the nature and sequence of the various layers, as developed by deposition or weathering, or both.

SOIL SCIENCE: The study of soils including soil formation, classification and mapping; physical, chemical, biological and fertility properties of soils; and these properties in relation to the use and management of soils.

SOIL STABILIZATION: Chemical or mechanical treatment designed to increase or maintain the stability of a mass of soil or otherwise to improve its engineering properties.

SOIL: In engineering, sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter. In soil science, the unconsolidated mineral or organic material on the immediate surface of the earth that serve as a natural medium for the growth of plants.

SOLAR RADIATION: The total electromagnetic radiation emitted by the sun.

STRESS: Intensity of force. The force per unit area acting within a mass.

- **EFFECTIVE STRESS** (**EFFECTIVE PRESSURE**) (**INTERGRANULAR PRESSURE**): The average normal force per unit area transmitted from grain to grain of a soil mass. It is the stress that is effective in mobilizing internal friction.
- **NEUTRAL STRESS** (**PORE PRESSURE**) (**PORE WATER PRESSURE**): Stress transmitted through the pore water (water filling the voids of the soil).
- **NORMAL STRESS**: The stress component normal to a given plane.
- **SHEAR STRESS** (**SHEARING STRESS**) (**TANGENTIAL STRESS**): The stress component tangential to a given plane.

STUBBLE: The basal portion of plants remaining after the top portion has been harvested; also, the portion of the plants, principally grasses, remaining after grazing is completed.

SUBSIDENCE: Settling or sinking of the land surface due to any of several factors, such as decomposition of organic material, consolidation, drainage, and underground failure.

SUBSOIL: The B horizons of soils with distinct profiles. In soils with weak profile development, the subsoil can be defined as the soil below the plowed soil (or its equivalent of surface soil), in which roots normally grow. Although a common term, it cannot be defined accurately.

TERRACE: An embankment or combination of an embankment and channel constructed across a slope to control erosion by diverting surface runoff water.

TILLAGE: The mechanical manipulation of the soil profile.

TRANSPIRATION: The process by which water in plants is transferred to the atmosphere as water vapor.

Unsat-H: Unsaturated Water and Heat Flow. A numerical water balance model developed by Pacific Northwest Laboratories.

WATER BALANCE: The sum of water in and passing through a landfill including storage of moisture in the landfill, input of moisture including precipitation and surface run-on, output of moisture including leachate, surface runoff, ET.

WATER CONTENT: In soil mechanics, the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles. In soil science, the amount of water lost from the soil after drying it to constant weight at 105°C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil.

WATER TABLE: The surface between the zone of saturation and the zone of aeration; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.

WATERLOGGED: Saturated with water; soil condition where a high or perched water table is detrimental to plant growth, resulting from over-irrigation, seepage, or inadequate drainage; the replacement of most of the soil air by water.

List of Acronyms

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
APAR	Affected Property Assessment Report
ARAR	Applicable or Relevant and Appropriate Requirement
AVGAS	Aviation Gas
bgs	below ground surface
BOD_5	Biochemical Oxygen Demand (5-day Test)
CAMU	Corrective Action Management Unit
CCL	Compacted clay layer
CEC	Cation Exchange Capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CIWMB	California Integrated Waste Management Board
CLU-IN	Hazardous Waste Clean-Up Information
COC	Contaminant (or chemical) of concern
COD	Chemical Oxygen Demand
CONUS	Continental United States
CSM	Conceptual Site Model
DOD	Department of Defense
EE/CA	Engineering Evaluation/Cost Analysis
EM	Environmental Management
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate model
ESTCP	Environmental Security Technology Certification Program
ET	Evapotranspiration
ETI	Environmental Technology Initiative
ETV	Environmental Technology Verification Program
FFRRO	Federal Facilities Restoration & Reuse Office
FFS	Focused Feasibility Study
FMC	Flexible Membrane Cover
FPP	Flexible Polypropylene
GCL	Geosynthetic Clay Layer
GLEAMS	Groundwater Loading Effects from Agricultural Management Systems
GM	Geomembrane
GSC	Guide Specifications for Construction
HDPE	High-Density Polyethylene

HELP	Hydrologic Evaluation of Landfill Performance computer model
HW	Hazardous Waste
K	Saturated hydraulic conductivity
LDR	Land Disposal Restrictions
LEA	Local Enforcement Agency
LLDPE	Linear Low-Density Polyethylene
MAP	Management Action Plan
MBALANCE	Water Balance Analysis Program
MSW	Municipal Solid Waste
MSWLF	Municipal Solid Waste Landfill
NAPL	Non-Aqueous Phase Liquid
NCDC	National Climatic Data Center
NCERQA	National Center for Environmental Research and Quality Assurance
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NELP	Naval Environmental Leadership Program
NETTS	National Environmental Technology Test Sites Program
NFA	No Further Action
NOV	Notice of Violation
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Association
OSWER	Office of Solid Waste and Emergency Response
PCB	Polychlorinated biphenyl
PCL	Protective concentration levels
PCLE	Protective concentration level exceedance
POE	Point of exposure
POTW	Publicly Owned Treatment Works
PP	Polypropylene
PRC	Public Resources Code
PRDA	Program Research and Development Announcement
PST	Petroleum Storage Tank
PVC	Polyvinyl Chloride
QAPP	Quality Assurance Project Plan
RAP	Response Action Plan
RB/PB	Risk-Based/Performance-Based
RBEL	Risk-Based Exposure Limit
RCI	Rapid Commercialization Initiative

RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial investigation/feasibility study
ROA	Research Opportunity Announcement
ROD	Record of Decision
RPM	Remedial Project Manager
RTDF	Remediation Technologies Development Forum
RWQCB	Regional Water Quality Control Board
SARA	Superfund Amendments and Reauthorization Act
SBIR	Small Business Innovative Research Program
SCS	Soil Conservation Service
SERDP	Strategic Environmental Research and Development Program
SITE	Superfund Innovative Technology Evaluation Program
SW	Solid Waste
SWRCB	State Water Resources Control Board
TAC	Texas Administrative Code
TCLP	Toxicity Characteristic Leaching Procedure ??
TDS	Total Dissolved Solids
TMV	Toxicity, mobility, or volume
TNRCC	Texas Natural Resource Conservation Commission
TOC	Total Organic Carbon
TPH	Total petroleum hydrocarbons
TRRP	Texas Risk Reduction Program
TSS	Total suspended solids
UIC	Underground Injection Control
UNSAT-H	Unsaturated Soil Water and Heat Flow Model
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USLE	Universal Soil Loss Equation
VCP	Voluntary Cleanup Program
VFPE	Very Flexible Polyethylene
VOC	Volatile organic compound